NREL
Transforming ENERGY

National Renewable Energy Laboratory History:

1977–2016

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Kimberly B. Adams
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Foreword

Like the political and energy landscape at the time, the birth of the Solar Energy Research Institute (SERI) in 1977, which then became the National Renewable Energy Laboratory (NREL) in 1991, was at times tumultuous. Born from a need for better energy solutions, the newly formed U.S. Department of Energy realized that creating an organization solely dedicated to clean energy was crucial to our nation's ability to achieve energy independence. Forty-five years later, the "little lab in the hills" is at the forefront of clean energy innovation and is helping tackle our most daunting energy challenges.

This book documents the creation of SERI and the politics and context of the times, from 1977 to 2016. It's the culmination of extensive independent research and formal oral history interviews—and it took more than a decade to complete. The "NREL History Project" was launched in 2009 to comprehensively record the birth and history of the laboratory to date. The project concluded in 2016 but was put on hold until 2021. The project team wishes to thank the many people who helped finally conclude the project through this publication.

The scope of the NREL History Project process was thorough and far reaching. Through a patented organizational history documentation process implemented by the project subcontractor, The History Factory, hundreds of hours of oral history interviews were conducted and recorded. Storylines were researched, validated, and written; and multiple, collaborative, facilitated sessions took place that included participation by nearly 60 former and current NREL staff and all former living and then-current NREL directors. These participants generously gave their time to help us develop the major storylines that are featured in this book. There are far more stories, many more nuanced, about the birth and growth of NREL that are not included in this book. We regret any omissions and always welcome further information and input.

A note about the artwork

The chapter and cover artwork are from a four-painting collection commissioned by SERI in 1979 and painted by NASA artist Robert McCall (1919–2010). Best known for his renditions of the United States space program—notably, the six-story moon landing mural that greets visitors at the Smithsonian's National Air and Space Museum—McCall's NASA-related art has been featured on U.S. Postal Service stamps as well as at the Pentagon and other science- and academic-related locations. In 2022, the paintings featured in this book were on display in the NREL Information Commons in the Research Support Facility in Golden, Colorado. While McCall is known for featuring actual people in his paintings, the SERI and NREL staff pictured here are a mystery.

McCall's artwork is colorful, iconic, and notably "futuristic." He envisioned a future world where clean energy featured prominently into our landscape, along with buildings, cities, computers, and public engagement that did not yet exist anywhere but in the artist's imagination. Today, we see an even brighter version of his vision—diversity in our energy industry, buildings that are beautiful and integrated into their landscape, living laboratories that are proving the "art of the possible."

We especially thank Randy Dins of the DOE Golden Field Office who was instrumental in ensuring that the NREL McCall paintings were carefully brought back to public view after languishing in storage for many years. Uncovering the brilliance and unique nature of these treasures would not have happened without his diligence and advocacy.

Featured in chronological order:

Perfect Weather for a Streamlined World

The Future Looks Bright

This Dream's In Sight

We'll Be Clean When Their Work is Done

Dedication

This book is dedicated to **Anne Jones** (1960–2017), whose enthusiasm and support for NREL were unwavering.

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"Perfect Weather for a Streamlined World"
Robert McCall, 1979

Chapter 1

Roots: Historical Context and the Creation of SERI

Introduction—Energy and the Environmental Movement

The CBS News special opened with Walter Cronkite and an idealized icon of the sun and sea—a spiky yellow wheel dipped in a wavy blue bowl.[1] As this graphic dissolved into a map of the United States, Cronkite began his tour, chronicling the nation's observance of a new holiday—Earth Day—on April 22, 1970.

Some felt that Earth Day was a distraction from the more pressing and polarizing concerns of the Vietnam War and civil rights. Some of Earth Day's teach-ins and demonstrations carried the same air of theatricality and mischief associated with the 1960s counterculture. Environmentalism was seen as a fad—the hippies could have their day, and then we'd return to business as usual.

Earth Day's 25-year-old national coordinator, Denis Hayes, had a ready response for the naysayers: "If the environment is a fad, it's going to be our last fad. We are building a movement, a movement with a broad base, a movement which transcends traditional political boundaries. It is a movement that values people more than technology, people more than political boundaries, people more than profit."[2]

A decade later, Hayes would be tapped to become the second director of the Solar Energy Research Institute (SERI), precursor to the National Renewable Energy Laboratory (NREL), an organization ***required*** to navigate the complex technology, politics, and profit motives that can be the instruments of our world's destruction—or its salvation. Nearly 50 years after the first Earth Day, these ideals of innovation, public-private partnerships, and cost parity are still being harnessed every day at NREL in service of a vital movement to help save the world.

ACT I—Overcoming the Oil Weapon

The roots of renewable energy sprouted from a confluence of politics and profits.

"To understand the early history of SERI, you have to go back to the mid-1970s and, specifically, to 1973 when the nation was in the upheaval from the Arab oil embargo in the summer and fall of that year," said Bob Noun, NREL's executive director of communications and external affairs.[3]

Until the early 1970s, large integrated oil companies had the upper hand in the world market, setting prices and scoring windfall profits. Arab nations had long been angry at this arrangement and formed the Organization of Petroleum Exporting Countries (OPEC) in 1960. But oil companies were much more powerful than OPEC at the time. Besides, America still had a robust domestic supply, it was thought—and would until at least 1985. In truth, crude oil production in the continental United States hit its peak in 1970, and by 1973, Saudi Arabia became the most powerful petroleum producer in the world.

> "To understand the early history of SERI, you have to go back to the mid-1970s and, specifically, to 1973 when the nation was in the upheaval from the Arab oil embargo."
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> – **Bob Noun**, NREL Executive Director of Communications and External Affairs

On October 6, 1973, OPEC leaders arrived at the Intercontinental Hotel in Vienna to negotiate a new price with representatives of major oil companies. That same day, Egypt and Syria launched an offensive on Israel that coincided with the start of the Jewish high holy day of Yom Kippur. "The enormity of the surprise of the Arab attack would be for the Israelis what Pearl Harbor had been 32 years earlier for Americans," wrote energy scholar Daniel Yergin.[4]

As the negotiations grew increasingly tense, the United States knew that any public aid for Israel would inflame the Arab oil ministers, not to mention embroil them in a Cold War proxy battle. However, the United States could not afford to let the Soviet Union, which was resupplying Syrian and Egyptian forces, turn the tide of Middle East politics. With Israel in dire trouble, Secretary of Defense James Schlesinger advised an airlift. Soon, American C-5A cargo planes landed on Israeli soil.

OPEC left the negotiating table and unilaterally raised the price of oil by 70%—to more than $5 per barrel. By week's end, Saudi Arabia cut off all oil exports to the United States, a full-scale launch of what became known as the "oil weapon."

"It revealed for the first time how vulnerable the U.S. was to supply disruptions of petroleum," Noun said.

Through the fall of 1973 and into 1974, American motorists waited in long lines at the pump for a few rationed gallons of gas. The price of crude oil rose to over $12 per barrel, making it clear to all Americans that we were now fully dependent on imports. OPEC was in the driver's seat.

"I sat in the gas line for five or six hours, as many other people did," said NREL Research Fellow Bob Thresher. "I really had sort of an anger that probably isn't quite subdued even today. I just didn't see any reason why we should be dependent on other people. It seemed like we should be able to generate our own energy one way or another. That was kind of a catalyst and I vowed that, the first opportunity I got, I was going to try and work to do something about that."[5]

Environmentalists had long felt that President Richard Nixon had dragged his feet on environmental policy. The White House had declined to participate in Earth Day, its attitude characterized as one of "benign neglect," CBS's Dan Rather reported at the time.6 With the oil crisis now at hand, Nixon announced Project Independence, an initiative to conserve and develop domestic energy sources—primarily nuclear and coal power—as well as ramping up domestic production of petroleum.

The Watergate scandal became Nixon's downfall, and he resigned in August 1974. President Gerald Ford's administration took up the energy self-sufficiency battle. The Ford administration took a different approach, though, focusing on what physicist Amory Lovins characterized as the "soft path" of energy efficiency and renewable sources, instead of the "hard path" of fossil fuels and nuclear energy.

In October 1974, Ford signed the Energy Reorganization Act, one of five major bills that abolished the Atomic Energy Commission and established the Energy Research and Development Administration (ERDA). Ford also signed the Solar Energy Research, Development and Demonstration Act of 1974, which specifically called for the establishment of SERI.

While working as a staffer for U.S. Rep. Tom Harkin (D-IA), then a member of the House of Representatives' Committee on Science and Technology, Noun had the opportunity to contribute to the latter piece of legislation. "This is a critical piece of the history of renewable energy—not just SERI—in the United States," he said, "because it, for the first time, put a powerful policy signal out there that we were going to attack our energy issues not only from a regulatory and legislative policy standpoint but to actually create a center for innovation to bring these technologies into the mainstream, into the marketplace."[7]

The soft path would by no means be an easy path, but renewable energy was finally a national priority. Now began the hard work of making renewables a technological and economic reality.

ACT II—Setting the Stage for SERI

While our recent reliance on petroleum may seem immutable, it is important to remember that humanity has repeatedly transitioned from one prevalent energy source to another. And while the term "renewable energy" may have only recently come into vogue, the concept is timeless.

Life on Earth relied on sunlight for eons, but the discovery of fire approximately 790,000 years ago is in some sense the earliest known instance of humans harnessing another renewable energy source—biomass—for warmth and illumination.8 Wood, peat, dung, and other combustible organic compounds served as humanity's go-to energy source for thousands of years.

Around 4000 BCE, early civilizations combined multiple kinds of biomass—a boat made from a wooden log, plus a sail made from animal skin—to harness another renewable energy source: wind. Native Americans, as well as ancient Greeks, Romans, and Asian cultures, settled near natural hot springs and made use of other geothermal features for warmth, cooking, cleansing, and healing. Windmills and watermills channeled natural currents into useful energy, with the Dutch further developing wind power in the late 16th century. But as population growth outpaced renewable technologies in the 17th century, the exploitation of nonrenewable resources began.

Sailing ships expanded, among many things, the whaling industry; one of its chief byproducts, whale oil, was used primarily as lamp fuel. By the end of the 18th century, coal power began to displace wood, wind, and water power.

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Though fossil fuels became the norm in the 1800s, research proved that alternatives existed. The discovery of electrolysis in 1800 was key to the development of the first hydrogen fuel cell in 1838. By the early 1830s, ethanol blends began displacing whale oil as lamp fuel. In 1839, French scientist Edmond Becquerel discovered the photovoltaic effect, the concept behind much of the modern solar energy industry.

Everything changed with Abraham Gesner's 1853 discovery of distilling kerosene from petroleum. Six years later, E. L. Drake struck oil in Titusville, Pennsylvania, initiating the country's first great oil rush. By the end of the 19th century, John D. Rockefeller's Standard Oil had complete control of the industry.

The advent of cheap, readily available petroleum relegated renewables to little more than research curiosities. Despite Albert Einstein's 1921 Nobel Prize for his theories on the photoelectric effect, solar energy could not power the machines of war or the engines of America's newest obsession, the automobile.

Between 1916 and 1918, the number of cars in the United States doubled. Even when the Great Depression hit, the oil business was booming in East Texas thanks to the "Black Giant," the largest oil reservoir in the contiguous United States.[9]

On the other side of the world, American oil companies began prospecting in the Saudi Arabian desert, striking oil in 1938. Though it took decades to realize the full potential of Middle Eastern oil, the promise of it was immediately understood—a year later came the outbreak of World War II, a global battle largely won and lost based on access to petroleum. However, the most lasting influence of World War II on the energy landscape was the advent of atomic power, which held considerable commercial promise but was clearly a most destructive form of alternative energy.

> “Everybody was bidding. There were 19 bidders, and every single one of them was considered.”
>
> – **John McKelvey**, former president and CEO of Midwest Research Institute

Postwar efforts around renewables led to Bell Labs developing the first successful silicon solar cell in 1954. The following year, President Dwight Eisenhower called for a “movement toward a fuller use of virtually unlimited energy of the sun.”[10] By 1960, the first large-scale geothermal power plant began operation in California.

While some dipped their toes in renewable energy waters, the question was whether domestic oil supply could keep up with demand. Indeed, during the 1960s, more oil was consumed than in all human history combined. Just as geologist and energy resource expert M. King Hubbert had famously predicted in 1956, the lower 48 United States reached peak oil in 1970, the same year as the first Earth Day. Though the country weathered the worst of the 1973–1974 oil crisis, it was by now clear to many that it was finally time to once again transition to a new energy paradigm.[11]

In his opening remarks at the 1974 World Energy Conference in Detroit—held on the 50th anniversary of Henry Ford's assembly line innovation—President Gerald Ford said:

> Everyone can now see the pulverizing impact of energy price increases on every aspect of the world economy. The food problem, the inflation problem, the monetary problem, and other major problems are directly linked to the all-pervasive energy problem. … It is difficult to discuss the energy problem without lapsing, unfortunately, into doomsday language. The danger is clear.[12]

While some 4,000 delegates from 69 countries attended that conference, nearly all were part of the Big Energy establishment, described by one reporter as “men with graying hair, conservative suits and ties, and the same lame ideas about energy.”[13] Alternative energy delegates were discouragingly underrepresented. Founding members of the American Wind Energy Association organized their own, smaller conference in a Detroit police station basement. As if to force the issue, they erected an illuminated, wind-powered billboard welcoming the invited representatives to the bigger conference across town.

The renewable energy community clearly faced an uphill battle. Nevertheless, only a month later, the Solar Research, Development, and Demonstration Act was passed on October 26, 1974, with the federal government offering what would become a SERI budget that “may reach or exceed $1,000,000,000.”[14] The level of government enthusiasm was now palpable.

It was Section 10 of the bill that explicitly outlined the establishment of SERI, leaving the institute's future home an open question.[14] The authors of the bill argued that temporary “micro locations” could be set up outside a main center that could address specific solar, wind, and other energy technologies. In March 1976, ERDA issued a request for proposal (RFP) from organizations interested in establishing and operating SERI, and in choosing the site of the main laboratory, the top criteria included: general transportation accessibility, neighborhood desirability for putative personnel and their families, and the availability of continuing education for personnel.

Competition immediately heated up, with major lobbying from more than a dozen states. Arizona, California, New Mexico, Florida, Texas, New York, Georgia, and a coalition of six New England states were seen as the major contenders. “Everybody was bidding,” recalled John McKelvey, former president and CEO of MRIGlobal. “There were 19 bidders, and every single one of them was considered.”[15]

In 1976, the Midwest Research Institute (MRI) submitted a proposal for SERI. Though, at the time, MRI was perhaps best known for its role in developing the coating for M&Ms, McKelvey said, “we were looking for fields that we could get into, and the solar field looked good to us, so we started putting some money into some research projects to build up our capabilities. And then the SERI RFP came out.”[16]

MRI first explored the possibility of partnering with Arizona, Florida, and Missouri before settling on Colorado as an ideal partner. Colorado Springs was initially chosen as SERI's proposed locale, but it soon became clear the city did not offer adequate transportation or PhD-level education opportunities. Governor Richard Lamm worked with MRI and the state legislature to find a new site, promising the required 300 acres of land could be donated from a Colorado Highway Patrol test site on top of South Table Mountain in Golden.

MRI had found its place. Next, it had to find its people.

McKelvey, along with MRI Senior Vice President (and future SERI director) Harold Hubbard, chose Princeton-based photovoltaic researcher Paul Rappaport as SERI's proposed director. Michael Noland, the director of MRI's engineering sciences division, was proposed as deputy director.

In addition to the 300-acre permanent site, MRI also offered the conveniently located Denver West Office Park as an initial site for SERI, pointing out the site's proximity to an international airport, the University of Colorado, and downtown Denver. But it was MRI's all-in dedication that set the institute apart amid a sea of other bidders, McKelvey said:

> We said MRI will totally commit itself to running SERI. We had board members come out to the presentation. The governor—Governor Lamm—was there, and we said we would form a special oversight committee of the MRI board to work with SERI, and that I would spend the vast majority of my time working on SERI, which I did for the next 23 years. When Battelle made their presentation, they said that this would be a big project for them, but it would just be one of many big projects. And the fact that we said that we would commit as much as we did, that carried the day.[17]

In March 1977, following what the Washington Post reported as “some unusually heavy political infighting,” the underdog emerged victorious.[18] MRI had won. This decision did not prevent more politics; however, the bill's concept of micro locations soon became a thorn in SERI's side. Four “satellite SERIs” were soon established, largely because of political associations with renewable energy champions: Massachusetts, because of U.S. Sen. Ted Kennedy (D-MA); Minnesota, because of former Vice President Hubert Humphrey; California, because of social activist Tom Hayden; and Georgia, because of President Jimmy Carter.[19]

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According to Alexis Madrigal, author of Powering the Dream: The History and Promise of Green Technology, “The Centers did not have a clear and defined purpose but instead siphoned off funds and focus from SERI's work. A close observer called the 'birth pains' of SERI 'a classical example of what happens when political expediency overtakes a basically sound idea.'”[20] McKelvey concurred, adding that all four satellites eventually “just kind of withered away.”[21]

SERI's larger challenge amounted to taking relatively primitive renewable energy technology and making it a reality. Bob Noun summarized the difficulty of diving into these untested waters of research and development:

> We had no technical precedence for these technologies that we were asked to produce at an extremely quick pace and at a large scale. … The second issue that we were up against was that we didn't have a ready pipeline of the kind of bright minds in the sciences and engineering specific to the work that we were going to do. So, we had to bring in—and we did bring in—a lot of bright people, chemical engineers, aerodynamicists, mechanical engineers who had worked on similar concepts but had no experience because there was none out there to work strictly on renewable energy technologies.[22]

As SERI prepared to commence operations, there were many questions and few answers. Fortunately, SERI's staff and supporters maintained huge stockpiles of a vitally important renewable resource—passion.

ACT III—The Challenge Ahead

The President's Report to the Nation opened with Jimmy Carter beside a crackling fire—flames dancing in a comforting hearth. It was February 2, 1977, less than two weeks into his presidency. As the camera zoomed in on the new leader of the free world wearing a beige sweater, perhaps symbolizing a simple way to stay warm after turning down the heat, President Carter began his informal fireside chat on energy.[23] “We will emphasize research on solar energy and other renewable energy sources,” he stated outright.[24]

On April 18, Carter unveiled his administration's full energy plan, which placed an emphasis on conservation, and reminded Americans of the collective sacrifice necessary to transition our energy consumption:

> Twice in the last several hundred years, there has been a transition in the way people use energy. … Because we are now running out of gas and oil, we must prepare quickly for a third change—to strict conservation and to the renewed use of coal and to permanent renewable energy sources like solar power.[25]

This time, the imperative was not merely lip service. In July 1977, SERI, the first-ever federal facility dedicated to developing solar power, commenced operation in Golden, Colorado, with Paul Rappaport as its inaugural director. A small staff began moving into temporary facilities in the Denver West Office Park. A month later, the Department of Energy was formed, with former Secretary of Defense James Schlesinger appointed as the first energy secretary. In October, "soft energy path" proponent Amory Lovins visited SERI. The following year, the institute welcomed Schlesinger and President Carter himself.

On May 3, 1978, the new holiday of Sun Day (like Earth Day, coordinated by Denis Hayes) brought nationwide sunrise services and events commemorating the dawn of a new solar age.[26] It was an inauspiciously cloudy and rainy afternoon in Golden (with plenty of wind!), but President Carter reminded attendees in his opening remarks, "Nobody can embargo sunlight. No cartel controls the sun. Its energy will not run out. It will not pollute the air; it will not poison our waters. It's free from stench and smog. The sun's power needs only to be collected, stored, and used."[27]

Easier said than done. SERI got to work.

While at SERI, President Carter observed some of SERI's early efforts, including solar photovoltaic systems, wind turbines, a biomass converter, and a model of a solar power plant. These were but a small sample of the many accomplishments of SERI's first year. Research at SERI was broadened to include both basic and applied research in not only solar but also biomass conversion, wind energy, passive solar, and energy storage. The institute also created the Solar Energy Information Data Bank, published its first annual review of solar energy, and held dozens of workshops and lectures. In 1980, SERI announced its first world-record solar cell.[28]

But it would not be a straight shot to success for the renewable energy industry. The Iranian Revolution in 1979 further destabilized the Middle East, the Three Mile Island disaster cast a pall on nuclear energy, and the beginnings of a new oil panic sent prices from $13 to $34 per barrel. Despite these challenges, domestic drilling in Alaska and a new administration in Washington brought the focus back to nonrenewables.

On April 21, 1980—the eve of Earth Day—SERI director Paul Rappaport died after a prolonged illness, and Denis Hayes was appointed his successor. Under Hayes' leadership, SERI's mission to hasten the transition from oil to renewables would soon hit another snag. While researching and developing more efficient, reliable, and cost-effective renewables would remain the primary challenge of the organization for decades to come, the secondary and sometimes more daunting challenges came in the form of political feuds, fluctuating funding, and uncertain national energy policy.

Changing the minds and actions of a world dependent on oil would not be easy, but the mission-driven people of SERI were up to the challenge.

> “On April 21, 1980–the eve of Earth Day–SERI director Paul Rappaport died after a prolonged illness, and Denis Hayes was appointed successor.”

"When I learned more about the purpose of the institute and understood more about the mission, I felt that it would be a place where I could meet a personal commitment that I had to make a difference," said 37-year NREL veteran Sylvia Motazedi.

Reflecting on President Carter's Sun Day visit, she added, "How often does an individual have the opportunity to be in the company of a president who is saying to the staff, 'You're doing the right thing. It's important for the economy, for the nation and the world'? I think he was right. That's why I'm still here."[29]

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"The Future Looks Bright"
Robert McCall

Chapter 2

Solar Photovoltaics

Introduction—The Gulf Between NASA and Novelty

In 1974, a year after the start of the first oil embargo by the Organization of Petroleum Exporting Countries (OPEC), a *National Geographic* reporter asked petroleum geologist M. King Hubbert if he could imagine a solution to the oil shortage. Hubbert, who had predicted peak oil, pulled a small fan from his pocket that was powered by a simple solar cell. "We have it already," Hubbert proclaimed, enjoying a modest breeze.[1]

Meanwhile, some 250 miles above Earth, a four-armed solar array traversed space like an extraterrestrial windmill, providing power to the prototypical orbital workshop, Skylab. After its first use on the Vanguard satellite more than 15 years earlier, high-efficiency solar energy was coming of age.

In 1977, most alternative energy existed on the far ends of the spectrum—high-efficiency, high-cost prototypes, or low-efficiency, low-cost novelties. Widespread residential or commercial use of solar energy was a distant dream. But the 1974 oil shortage spurred the nation to try to make this dream a reality. In 1977, the U.S. Energy Research and Development Administration established the Solar Energy Research Institute (SERI), a new laboratory in Golden, Colorado, with a mission to lower solar costs and improve efficiency while researching and developing next-generation advances that could turn fantasy into reality.

ACT I—An Institute for Solar Research and Development

In 1954, three scientists from Bell Labs developed the first silicon photovoltaic (PV) cell—a rudimentary device with only 6% efficiency. They were able to double the efficiency in just 18 months, but "a 1-watt cell cost almost $300 per watt in 1956, while a commercial power plant cost 50 cents a watt to build at that time."[2]

A little less than 25 years after its invention, silicon PV dipped to about $77 per watt. But in the early 1960s, the cost of high-efficiency crystalline silicon modules was still nearly $500 per watt,3 due largely to production complexity:

The manufacturing steps of purifying silicon to a very high level, growing it into single-crystal ingots, sawing the very hard material into wafers, making solar cells out of the wafers, where each cell produced less than half a watt, and finally stringing these together and encapsulating [them] into modules, was deemed hopelessly expensive.[4]

In 1977, SERI's first onsite PV laboratory became operational, with lead researcher Larry Kazmerski articulating the goal of "increasing reliability and efficiency and decreasing the cost of photovoltaic solar cells."[5] The lab focused on developing both crystalline silicon cells and lower-cost thin-film devices.

While historically less efficient, thin-film materials use significantly less active material in their energy conversion compared to crystalline silicon cells. So, SERI began performing research and development (R&D) on thin-film technologies—amorphous silicon, copper indium diselenide, and cadmium telluride—hoping this would help reduce the cost of solar energy.

During SERI's first year, a key focus was investigating new ways to purify silicon and reduce raw material costs.[9] SERI also gathered and disseminated research, including resurrecting about 6,000 solar patents, some dating back to the 1800s.[10]

The following year, the Carter administration passed the Solar Photovoltaic Energy Research, Development, and Demonstration Act of 1978, which set forth the aggressive goal of reducing the average cost of solar PV systems to $1 per watt by 1988.[11] SERI had its marching orders.

According to SERI's second director, Denis Hayes, part of SERI's innovation strategy in the late 1970s was "to get someone on the producer side to make solar technology, and then get someone on the consumption side to use it."[12] In support of the idea of domestic producer-consumer partnerships, President Carter signed the National Energy Act, which included the Public Utilities Regulatory Policy Act (PURPA), a pivotal piece of legislation that helped establish the renewable energy industry.[13] The policy required utilities to buy power generated by small-scale renewable facilities at higher retail (not lower wholesale) prices, which provided incentives for both small investors and large corporations to build or invest in renewables. The legislation jumpstarted innovation, but the high costs of these PURPA projects didn't always yield cost savings for end users. Nevertheless, in 1980, ARCO Solar built the first commercial PV facility capable of producing more than 1 megawatt, which went online in 1982.

PURPA facilitated greater investment in available technology, and the Bayh-Dole Act of 1980 updated the patent and trademark system, stimulating licensing of federally funded innovations.[14] Together, these two policies crafted a new framework for successful technology transfer—guiding innovation from basic research to prototype and finally to commercially viable technologies—where researchers and institutions reaped the rewards of success.

THE COST OF SOLAR ENERGY

According to data collected by the U.S. Department of Energy, the average retail price of residential electricity was 12.5 cents per kilowatt-hour (kWh) in 2014. That price had reached a low of about 9 cents per kWh in 1973, but the two oil shocks of the 1970s brought the price up to 12.5 cents per kWh by 1983 (historic prices adjusted for inflation).[6]

During the late 1970s and early 1980s, prices increased even as consumption decreased. In 1982, the average annual residential energy bill was about $2,583 (in 2014 dollars), or $215.22 per month.[7] In 2014, this figure was $1,322, or $110.20 per month—about half as expensive as 1982.[8]

There are many ways to dive into these averages and get more specific—how the price of electricity differs based on state, subsidies, weather, time of day, etc.—and the calculations can become quite complex. Three important factors to keep in mind:

- The price per kilowatt-hour for an end user to consume energy is partially dependent on the cost per watt for a utility or other system to generate power.
- The more efficiently a technology can convert incident solar energy into a usable form, the more kilowatt-hours it can produce per square meter of PV module area. Thus, a more expensive—yet more efficient—module might ultimately result in a lower price per kilowatt-hour than a cheaper but less efficient system.
- The size of a system can deliver economies of scale that allow higher-efficiency modules to become more cost effective.

Here, we focus primarily on the evolving cost per watt—for utility-scale power generation specifically—as a key driver of what makes a PV energy source viable in the greater marketplace. Key drivers of cost per watt are the efficiency of the technology, the costs of manufacturing and installation, the economies of scale associated with large utility-scale operations, and the lifetime of the PV system.

> “In 1977, SERI's first onsite PV laboratory became operational, with lead researcher Larry Kazmerski articulating the goal of **"increasing reliability and efficiency and decreasing the cost of photovoltaic solar cells.**”

In 1980, thin-film solar cells achieved 10% efficiency, and the price of silicon PV dropped to less than $30 per watt.[15] Despite these advances, the clean-energy momentum of the Carter administration began to fizzle. The 1978 Carter budget allocated only about one-fifth as much funding to solar, wind, and biomass combined as it did to nuclear R&D and, by 1980, this dwindling support was becoming even more evident.[16]

Meanwhile, nuclear power made headlines with the first of several disasters. At the Three Mile Island nuclear facility in Pennsylvania, a loss of coolant and partial meltdown of the reactor's core led to a release of radioactive steam in March 1979. This accident might have shifted goodwill toward renewables, but some PURPA-driven investments were quickly becoming, according to energy economist Daniel Yergin, "miniature white elephants," giving the renewable energy industry an unfortunate black eye.[13]

When Ronald Reagan entered the White House in January 1981, he reduced the SERI budget by more than half, cut a third of its staff, and appointed Harold Hubbard its director. An important program with Saudi Arabia, the SOLERAS program, was transferred from SERI to MRI because, according to a 1982 issue of the lab newsletter, *SERIscope*, "SERI's mission no longer includes programs for this type of technology transfer."[17] Indeed, long-term, high-risk research became SERI's new mandate. "We're going to produce a yeasty research and development environment here," Hubbard said. "One that won't be confused with an advocacy group or a special interest group."[12]

SERI was awarded its first patent on July 14, 1981, for a concept developed by Gene Blakeslee and Kim Mitchell. The concept involved boosting the conversion efficiency of solar cells by forming a sandwich of at least two active layers of solar cell material, each able to capture a different portion of the solar spectrum.[18] Then, starting in 1984, SERI's Jerry Olson invented and, with his colleague Sarah Kurtz and other coworkers, developed the first truly practical multijunction cell, based on the semiconductor materials gallium indium phosphide (GaInP) and gallium arsenide (GaAs). This work served as the basis for record-setting solar efficiency numbers in the coming decades and forms the basis of all modern solar cells used to power satellites.

In 1982, solar PV dipped below $20 per watt; the following year, SERI verified an 18%-efficient crystalline silicon cell. Although SERI's mission had been refocused on basic solar research, the institute had, by 1983, committed to expand its scope to include wind, biomass/alcohol fuels, solar thermal, hydrogen, ocean energy, and buildings conservation in addition to PV. The great challenge was making each of these technologies efficient, reliable, and cost effective.

ACT II—Basic Research and Tech Transfer

The 1980s were tough times at South Table Mountain. SERI's funding and staffing flatlined at $50 million and 500 employees, respectively. "The approach that was taken was, 'Let's keep our heads down,'" said NREL researcher Stanley Bull. "'Let's just do good, solid research. Then, over time, we'll manage to survive: number one. Number two: grow some. Then, over time, get back to the point of linking with industry and supporting industry to evolve these technologies into commercialization.'"[19]

During these lean years, the institute quietly achieved some impressive feats in R&D and laid solid groundwork for partnering with private industry to bring innovations into practical use.

Following in the footsteps of the Stevenson-Wydler Technology Innovation Act and the Bayh-Dole Act of 1980, the Federal Technology Transfer Act of 1986 allowed federal labs to enter into a consortium and negotiate licensing agreements for their patented technologies, known as Cooperative Research and Development Agreements (CRADAs). Two years later, the Alternative Motor Fuels Act created incentives for manufacturers to produce vehicles that could run on ethanol and methanol made from biomass or natural gas.[20]

Back in the lab, SERI researchers forged ahead. Between 1984 and 1985, the lab logged three industrial research/R&D 100 Awards—generally recognized as the "Oscars of Invention." These included one for a copper indium diselenide solar cell—developed in tandem with Boeing—that achieved a then-record 11.1% efficiency for thin-film solar PV.

No fewer than 20 startup companies emerged from SERI R&D during the 1980s. SERI's Photovoltaic Test and Measurement Laboratories became the industry's gold standard for analyzing the reliability and efficiency of new PV technologies, which had dropped to less than $10 per watt by 1987.

In 1989, SERI won the Federal Laboratory Consortium's Excellence in Technology Transfer Award for its work with amorphous silicon PV,[21] the same inexpensive technology first introduced in solar-powered calculators. One of SERI's spinoff companies became a subsidiary of Glasstech of Toledo, Ohio, having commercialized a process for manufacturing amorphous silicon PV modules on glass substrates. By the decade's end, as some PV technologies were nearing 25% efficiency, the cost had dropped again, to $6 per watt.

Though oil prices plummeted to about $10 per barrel in 1986, the nuclear disaster at the Chernobyl nuclear facility in Ukraine and the Exxon Valdez oil spill in Alaska served as stark reminders of the true cost of nonrenewables. During the 1988 presidential race, both major-party candidates campaigned as environmentalists.[13] After being elected to office, President George H. W. Bush increased SERI's funding and appointed Duane N. Sunderman as the institute's new director.

On the morning of September 16, 1991, President Bush welcomed Sunderman to the Roosevelt Room of the White House. He reminded U.S. Department of Energy (DOE) leadership and members of Congress of the importance of renewable energy and directed SERI to "translate our success in the lab into progress in the marketplace."[22]

Bush lauded SERI for its R&D and technology transfer and elevated SERI to the status of national laboratory. The institute's name changed to the National Renewable Energy Laboratory, or NREL. Funding and staffing increased considerably, and ground was soon broken on a $20 million permanent Solar Energy Research Facility.

NREL's new mandate was to help overcome two major obstacles in the quest for the widespread adoption of renewable energy. The first, the so-called "technological valley of death," refers to what is often time-consuming research that supports the proof of concept for new technologies. "Most companies cannot invest in research that could be a decade away from a commercial product," said Bill Farris, NREL's Associate Laboratory Director for Innovation, Partnering, and Outreach. Once market viability is established, the second major barrier, known as the "commercial valley of death," calls for national labs to support private industry in developing cost-effective, reliable ways to scale up this proven technology.

For solar PV, this market viability depends on creating more efficient, more reliable, and less expensive solar cells. After being elevated to national laboratory status, NREL remained at the forefront of record-setting efficiency. The lab's GaInP/GaAs multijunction concentrator cells, invented by Jerry Olson at SERI in 1984 and continually developed at SERI/NREL since then, were the first practical PV cells to break 30% efficiency, while cadmium telluride (CdTe) technology raised the efficiency of thin-film PV to more than 10%.

Among the eight R&D 100 Awards that NREL earned during this period, the lab's work to develop a CdTe PV module manufacturing process in 1991 stands out. By 1996, industry partner Golden Photon had produced a 25-kW CdTe solar array for the U.S. Navy, the largest in existence at that time. The CdTe thin-film technology and manufacturing process led to the launch of First Solar LLC, which would ultimately become one of the global leaders in low-cost thin-film solar cell manufacturing.[13]

NREL won another 16 R&D 100 Awards between 1993 and 2000 and set a new record for thin-film PV in 1996 with the 17.7%-efficient copper indium gallium diselenide (CIGS) technology. Despite these successes, Congress made severe cuts at DOE and NREL in the mid-1990s.

Meanwhile, in a global energy economy, the United States began to face stiff competition from abroad. In the late 1990s, innovators in Japan and Germany emerged as the most advanced PV manufacturers and, by the early 2000s, China became the solar industry's leading producer.[13] By 2002, as solar PV dipped to around $3 per watt, the United States lagged behind much of Asia and Europe, as well as Indonesia, New Zealand, and many other nations, in renewable energy growth.

ACT III—Getting to Grid Parity

U.S. manufacturing of solar PV received a huge boost in 2003, when NREL and First Solar collaborated on a high-rate vapor deposition technology that could deposit a thin layer of CdTe material onto a surface in less than 40 seconds. This was lightning speed compared to previous methods. The innovative process became an immediate landmark in solar PV history—finally, thin-film solar modules could be mass-produced.[23]

As the cost of PV modules dropped to $2.50 per watt, solar energy approached "grid parity," a term that emerged around the turn of the millennium that refers to the notion that a renewable technology can "compete head to head with electricity from the local utility and come out cheaper, or at least equal."[13] If it were achieved, grid parity was anticipated to facilitate broad commercial use.

During the preceding decade, NREL had established two collaborative facilities to hasten this commercial adoption by addressing the technological and commercial valleys of death in solar PV. The Outdoor Test Facility (OTF) and Process Development and Integration Laboratory (PDIL), completed in 1996 and 2006, respectively, brought together researchers, tools, data, and materials across multiple disciplines. Their goal was to improve the devices, manufacturing methods, and measurement techniques of solar PV. Today, the OTF works with the renewable energy industry to foster uniform standards of testing and measurement, evaluating prototypes and market-ready solar modules.

On February 1, 2006, nearly 30 years after President Jimmy Carter inaugurated Sun Day at the SERI campus, President George W. Bush became the second president to visit NREL, leading a panel discussion on his Advanced Energy Initiative that included a 22% increase in clean energy research at DOE.[24]

However, the United States was still catching up in the global clean energy playing field. In 2005, China's Renewable Energy Law supercharged its own alternative energy industry, following in the footsteps of Germany's Renewable Energy Law, which was enacted in 2000. Amid fierce competition, a German company became the top manufacturer of PV worldwide by 2007, but the leading force in achieving grid parity had shifted from Japan and Germany to China. "During 2006, about 12 different Chinese manufacturers went public," said Charlie Gay. "The majority of manufacturing today is across Asia."[25]

Following the Great Recession, the American Recovery and Reinvestment Act of 2009 allocated about $16.8 billion to DOE's energy efficiency and renewable energy programs, including $3.5 billion for solar, wind, geothermal, and biofuels projects.

Once again, manmade environmental disasters strengthened the case for clean, safer renewables. In 2008, a dike failure at Tennessee's Kingston Fossil Plant led to the worst coal ash spill in U.S. history, followed by the BP Deepwater Horizon oil spill of 2010. A month before the Fukushima nuclear disaster of 2011, DOE announced its ambitious SunShot initiative to reduce the installed cost of utility-scale PV to roughly $1 per watt by 2020, a figure that requires module production costs of less than 50 cents per watt.

> “On February 1, 2006, nearly 30 years after President Jimmy Carter inaugurated Sun Day at the SERI campus, President George W. Bush became the second president to visit NREL.”

Having produced 1 gigawatt of PV modules in 2009 alone, First Solar continued to drive toward grid parity, announcing in 2009 the major milestone that its CdTe PV cells could be manufactured for 98 cents per watt.[26] First Solar installed its 10 millionth PV module in 2012 and continued work on a far-reaching, 2.7-gigawatt pipeline of utility-scale solar projects. With continued competition from China, thin-film PV dropped below 50 cents per watt; subsequently, First Solar asserted it could manufacture for less than 40 cents per watt. Higher-efficiency crystalline silicon modules dropped from $4 per watt in 2007 to 50 cents per watt in 2014.[27]

Along with advanced depositional techniques pioneered by NREL and First Solar, significant cost and efficiency gains were also made in the testing of manufactured wafer silicon cells, thanks in large part to key innovations by principal engineer Bhushan Sopori.

In 2011, after 20 years of research and 12 patents, Sopori worked with industry partner AOS Inc. to create a manufacturing-scale optical cavity furnace (OCF). Likened to a microwave oven that can uniformly and efficiently target its energy on crystalline silicon wafers during processing, the OCF uses less energy and boosts the conversion efficiency rates of its solar cells by multiple percentage points. The OCF soon became capable of processing 1,200 wafers per hour, all without the constant, labor-intensive recalibrating required by previous manufacturing methods.

Two years later, Sopori and colleagues further improved the manufacturing process with NREL's Silicon Photovoltaic Wafer Screening System. The intense process of creating PV cells typically stressed between 5%–10% of the raw silicon wafers past their breaking point. Sopori's new screening system passed the wafers through a high thermal stress conveyor belt, "a lot like the toasting belt that turns a cold sub sandwich into a warm one," to weed out defective wafers before they are moved into the costly manufacturing process.[28] These temporary rejects are then melted down for reprocessing, saving those doomed to fail and their associated costs.

By 2015, solar PV had passed 25% efficiency for crystalline silicon and 20% for thin-film technology—in part due to manufacturing innovations like those described here—with First Solar exhibiting a 21.5%-efficient research cell in January 2015.[29] With these efficiencies, the goal of solar PV reaching full grid parity was in sight.

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"This Dream's In Sight"
Robert McCall

Chapter 3

Wind Energy

Introduction

In the early 17th century, Cervantes' well-meaning protagonist, Don Quixote, spotted 30 or 40 windmills from afar. Believing them to be "hulking giants," Quixote charged, and as he "drove his lance-point into the sail the wind whirled it round with such force that it shivered the lance to pieces."[1] The rotor blade proved stronger than the sword, and the idiom "tilting at windmills" has since been synonymous with fighting imaginary adversaries.

On the contrary, the modern field of wind energy presents a diverse array of clear challenges—structural, environmental, economic, behavioral, and systemic. Shortly after the Solar Energy Research Act of 1974 created the Solar Energy Research Institute (SERI), an independent committee produced a report outlining the organizational structure and personnel needed to take on these challenges:

> In regard to wind power, [SERI] will need hardware-oriented groups to assess the probability of success and the life of machines that are under development. It will need structural and civil engineering groups to assess installation costs, scientists working on corrosion to try to understand the salt-spray problem, life scientists to deal with bird avoidance and to help set acceptable limits on noise from wind machines, systems people and solid-state power engineering to look at the role of storage and the coupling of wind machines to the utility net. SERI personnel should define standard specifications for the rating of wind machines and should develop or assemble convenient tools for the routine assessing of wind resources at specified sites. Finally, SERI could set standards for the collection of wind data which might be useful in the solar-energy data bank.[2]

ACT I—Establishing a National Program

Less than a decade before SERI commenced work, the international wind energy industry was virtually nonexistent. In 1968, President Lyndon Johnson broadened the National Science Foundation's (NSF's) mission, leading to the launch of NSF's Interdisciplinary Research Relevant to Problems of Our Society, with elevated funding for environmental and energy projects. In 1971, under President Richard Nixon, this program was expanded to the ambitious and interdisciplinary Research Applied to National Needs (RANN), organized around specific problems of the time—including pollution, transportation, and energy—rather than science disciplines.[3]

To address the energy issue, the NSF partnered with the National Air and Space Administration (NASA) in 1972 to organize the Solar Energy Panel—comprised of 40 interdisciplinary engineers and scientists from academia, industry, and government. Their goal was to assess the raw potential of various alternative energy sources.[4] While solar photovoltaic conversion was the focus of their work, wind energy was another promising element of the panel's inquiry. It concluded that wind had the potential to supply up to 19% of the country's annual energy requirements by the year 2000.[5]

As a next step, the NSF and NASA hosted a far-reaching wind energy workshop in Washington, D.C., from June 11–13, 1973. It was a time of renewed faith in American ingenuity and renewed awareness of American vulnerability: Only a month earlier, NASA celebrated the successful launch of Skylab, America's first space station. Several months later, the country would find itself embroiled in the Organization of Petroleum Exporting Countries (OPEC) oil embargo and the resulting energy crisis.

Aside from NASA and NSF leaders, this list of attendees included representatives from aerospace corporations, such as Grumman Aerospace and Boeing Vertol Company, which had taken a leading role in the Space Race and were well suited to help pioneer wind energy systems.5 Many believe that if private-public partnerships had worked for the Moon Shot, they could also work for wind turbines. After all, creating commercial-scale turbines would require similar mastery of disciplines, such as mechanical engineering, fracture mechanics, and environmental science, not to mention systems integration and project management.

Although wind energy conversion was, in the words of RANN Director Alfred J. Egger, "an ancient technology that has essentially lain fallow for more than a generation," several industry luminaries attended the NSF/NASA workshop, and their pioneering work provided a sound foundation for SERI and the next era of wind science and technology.

Harnessing the power of the wind is indeed an ancient practice, but the conversion technology's origins are hard to pinpoint. Vertical-axis (i.e., eggbeater) windmills were erected in 10th century Persia, where they helped drive water for irrigation, while horizontal-axis (i.e., pinwheel) windmills, often used to grind grain, prevailed in Europe from the 12th through 20th centuries.[6] The major shift occurred in the late 19th century, however, when wind machines began turning electricity generators.

A turbine's "capacity rating"—described in kilowatts (kW)—is its ability to produce a specific amount of electricity per hour when exposed to an optimal wind speed. What constitutes smaller-scale "distributed" power versus larger "utility-scale" power has changed over time depending on multiple factors. For our purposes, we will consider utility-scale generation to be 1 megawatt (MW) or higher (i.e., a power plant capable of generating 1 million watts—enough electricity to power about 1,000 small houses using 10 100-watt light bulbs each).

In 1888, Cleveland industrialist Charles F. Brush invented a landmark apparatus that produced 12 kW of power that he used for his mansion's 350 incandescent light bulbs. Around 1895, Danish professor Poul LaCour became one of the first proponents of the wind tunnel, which he used to test four-bladed rotors. The resulting LaCour windmills generated between 5 kW and 25 kW of electricity, and several hundred were produced and used through the early 1900s. Scientist Albert Betz then conducted wind tunnel testing in the 1920s to examine the aerodynamics of rotor blades and calculated the theoretical limit for wind energy conversion: the so-called "Betz's factor" of 59.3% maximum efficiency.[7]

Beginning in 1931, brothers Marcellus and Joseph Jacobs manufactured thousands of three-bladed "Jacobs Wind-Driven Electric Generating Plants," which produced 2.5–3 kW of power and were typically used on remote farms or in villages that were not yet on the grid. The same year, Russian engineers constructed one of the earliest utility-scale wind turbines at Balaclava: a two-bladed, 30-meter (m)-diameter wind turbine generating 100 kW of power.

Ten years later, Palmer C. Putnam partnered with the S. Morgan Smith Company to begin construction on a two-bladed 53.3-m-diameter turbine capable of driving up to 1.25 MW of alternating current (AC) power to the electrical grid. Atop a Vermont hill known as Grandpa's Knob, the wind turbine went online in October 1941. Though a series of structural cracks and fractures ultimately halted operation in 1945, "the Smith-Putnam wind turbine demonstrated through more than 1,000 hours of operation that a megawatt-scale wind power plant—a quantum jump from all previous wind machines—could operate in conjunction with a central power station and supply a significant amount of utility-quality AC power."[6]

Another notable contributor to early wind turbine development was German engineer Ulrich Hütter. Trained as an aircraft designer before World War II, Hütter shifted to wind turbines after aircraft construction was banned in postwar Germany. Hütter "was the first to transfer the principle of airfoil aerodynamics of airplanes to rotors of wind turbines," aiming for lightweight but highly durable construction.[7]

> “As the nation reeled from the OPEC oil embargo and energy crisis, the U.S. Federal Wind Energy Program was established in 1973.”

Hütter was also one of the first proponents of aesthetic excellence in turbine design, stating that the wind systems must "in a deeper sense be of a timeless beauty, so that they do not in three or four decades hence burden a later generation with the heavy task of removing angular skeletons."[8] In partnership with West Germany's Allgaier-Works, Hütter completed multiple turbines, including one of the first offshore machines—a 10-m-diameter, 10-kW wind turbine in the Gulf of Mexico—and a 35-m-diameter, 100-kW wind turbine that ran from 1961 to 1966.

Hütter attended the 1973 NSF/NASA workshop. So did Marcellus Jacobs (cocreator of the Jacobs Wind Electric Power Plant) and Beauchamp Smith (retired president of the S. Morgan Smith Company). The event also included contributions from Bob Thresher, a future NREL research fellow, often referred to as "the grandfather of American wind energy."[9] At the time, Thresher was an assistant professor at Oregon State University and his senior colleague, Robert E. Wilson, presented Thresher's "Cost Summary of the Putnam Design for 1945 to 1971," analyzing what the machine would have cost if built around the time of the workshop.[10, 11]

As the nation reeled from the OPEC oil embargo and energy crisis, the U.S. Federal Wind Energy Program was established in 1973, with a two-pronged vision: harnessing wind as a small-scale power source for suburban and rural homes as well as a supplement to coal, oil, hydroelectric, and nuclear power for large utilities.[12]

NASA's Lewis Research Center in Sandusky, Ohio, focused on the larger, utility-scale prototypes, 13 of them in all. The first was the MOD-0 experimental wind turbine, based on Hütter's designs, a 38-m-diameter test bed capable of generating 100 kW. These prototypes steadily upped the ante, with MOD-2—designed, built, and installed by Boeing—constituting the next generation, rated at 2.5 MW. The four MOD-2 turbines included many design improvements, such as pitched blade tips, a lighter tower and gearbox, and a teetered rotor (a hinged connection of blades to the hub, creating reduced loads and vibration).[13] Larger wind turbines completed through the NASA program included a 100-m-diameter turbine and another capable of producing 4 MW of energy. Bob Thresher summarized some of the program's findings:

It's counterintuitive, actually. The simple engineering idea is that your energy capture grows with your rotor size, so it grows with the diameter squared, but the weight and cost typically grow as the diameter cubed. So, there's a crossover point where you should have an optimum machine. … Something around 2 or 3 MW was probably the right size, with a rotor diameter of roughly 100 meters, would perhaps be optimum.[14]

Though tremendous learning came out of the NASA program, no clear-cut winner emerged in terms of a commercially viable and scalable wind turbine.

SERI analyzed some of the multimegawatt systems while developing and testing very small turbines of 1 kW–5 kW on-site. SERI also led a project area known as Advanced and Innovative Concepts, looking at highly experimental design improvements, like diffuser-augmented wind turbines (likened to placing a funnel in front of a turbine to induce more airflow through the rotor). Lastly, SERI investigated the environmental and institutional impact of wind turbines, especially in regard to noise pollution and economic value to utility companies.[12]

"We had no technical precedence for these technologies that we were asked to produce and at an extremely quick pace and at a large scale," said Bob Noun, who arrived at SERI in 1979 and served as the institute's first Wind Program manager.[15]

Not far from SERI's location in Golden, Colorado, Rockwell International operated the new Rocky Flats test site, which took on a much larger part of the federal wind program. Between 1977 and 1981, Rocky Flats oversaw the development and testing of about two dozen small wind system prototypes, ranging from 1 kW–40 kW. The site also undertook applied research on wind turbine aerodynamics, structural dynamics, airfoils, and variable-speed innovations.[12]

> “We had no technical precedence for these technologies that we were asked to produce and at an extremely quick pace and at a large scale.”
>
> – **Bob Noun**, who arrived at SERI in 1979 and served as the institute’s first Wind Program manager

The early 1980s brought a burst of activity around the study of wind turbines. Unfortunately, while the commitment was palpable, the challenges of creating economical and reliable turbines still remained enormous.

ACT II—Reducing Costs

In 1980, the price of wind energy hovered around $550 per megawatt-hour (MWh).[16] This cost calculation was due predominantly to the capital cost of constructing and installing the turbine, plus monitoring and maintenance associated with operating it for years to come. The performance of the wind turbine—how much electricity it was able to generate—further influenced the levelized cost of wind energy (LCOE).

While a downward trend in cost presented itself in the late 1970s, the funding cuts of the Reagan administration—from $50 million to about $5 million—seemed to signal an end to the Federal Wind Energy Program and foreshadow another fallow period for the renewable technology. Federal and state tax credits, especially in California, all but saved the nascent wind industry.

Under California Governor Jerry Brown, utility companies were required to buy power generated by wind projects, among other renewable sources. According to energy expert Daniel Yergin:

The result was California’s extraordinary wind rush. Committed wind advocates, serious developers, skilled engineers, and practical visionaries were joined by flimflam promoters, tax shelter salesmen, and quick-buck artists. Thus was the modern wind industry born. The frenzy gave rise to a critical innovation. Rather than depend upon a single mammoth machine, as Palmer Putnam had, smaller turbines were clustered together and connected by a computer network so that they functioned as though they were a single machine. These networked wind turbines became known as wind farms.[17]

California wind farms in the Altamont Pass, Tehachapi Pass, and San Gorgonio Pass began generating substantial amounts of electricity, but for every successful wind farm there were numerous instances of structures that could not withstand high winds. Many companies failed, but a small handful, including Zond, U.S. Windpower, and the Danish company, Vestas, emerged as reliable leaders. The only thing keeping the international wind energy industry afloat—and somewhat under the radar—was the industry’s cooperative spirit. After the Reagan cuts, international partnerships continued, with many of the California wind farm turbines being manufactured and shipped from Denmark.

On October 1, 1984, Reagan budget restrictions led to the Small Wind Energy Conversion Systems Program at Rocky Flats being merged into the Wind Energy Program at SERI.[18] Thresher arrived at SERI in 1984 to help unify the teams and move them forward. “The consolidation of that group caused a lot of hard feelings,” Thresher said. “People were losing their jobs. … And, if I did anything, I guess, I came in with a fresh look. And we kind of turned away from the big machines and started working with the small industry in California directly trying to pull people together to form teams.”[19]

Under Noun and Thresher’s leadership, Federal Wind Energy Program researchers convened with industry representatives to form the Cooperative Field Test Program (CFTP), which aimed “to enhance the technology transfer process.”[20] Aside from the advantageous cost-sharing model, the data obtained during the program was deemed highly valuable to both researchers and the industry at large.

Many key advances emerged during this period. First was a new modeling code—known as the FLAP code—developed by Thresher and former Oregon State colleague Bill Holley. According to Thresher, earlier codes, like the PROP code, based on converted helicopter propeller models, “addressed how much energy could be captured, and the FLAP code addressed how strong the blades need to be to withstand the forces acting on them, using simplified aerodynamics from PROP,” while adding the concept of turbulence and the amplifying effect of wind gusts.[10] The FLAP code soon became an industry standard modeling tool.[21]

SERI’s Structural Testing Facility for wind systems opened in 1989. With the institute’s mission continuing to grow, President George Bush elevated the organization to national laboratory status in 1991. That same year, the newly named National Renewable Energy Laboratory (NREL) won its first wind-related R&D 100 Award. NREL’s turbine blade airfoils—designed specifically for wind turbines rather than aircraft and able to run at maximum efficiency through strong winds—produced up to 30% more electricity than previous designs. Three “families” of airfoils for rotor blades of 1–25 meters were soon licensed by industry leaders.

By the mid-1990s, the wind LCOE had dipped from over $500/MWh to around $100/MWh, but despite U.S. improvements, Danish companies led the industry. In 1994, Thresher and NREL Wind Program manager Ron Loose traveled to the Risø Laboratory in Denmark, about 50 miles west of Copenhagen. Looking out the window of the Risø program director’s office, Thresher and Loose saw a row of offshore wind turbines spinning from strong fjord winds. Loose was astounded, and Thresher recalled his reaction:

“Bob,” he said, “This is what we need. We need a place where it’s really clear what kind of research you’re doing. We need to somehow figure out how to build a center where it’s a one-stop shop. Industry can come in and work with you. We can do research. We can test turbines. We can do what we need to do to move this technology along.” That was his vision.[22]

Unfortunately, shifting political winds back home portended that the Rocky Flats facility was about to be closed. NREL worked with Assistant Secretary of Energy Mike Davis to keep the facility and get the land transferred over to NREL so that it could pursue the kind of work the CFTP had done years earlier.

The result was the National Wind Technology Center (NWTC), dedicated by U.S. Secretary of Energy Hazel O’Leary in 1994. Ron Loose served as the center’s first program manager. Slowly, the NWTC built up its capabilities, adding a blade test facility and a state-of-the-art 2.5-MW dynamometer facility in 1994 to stress-test both blades and drivetrains of all sizes of wind turbines.

NREL worked with Zond during this period, helping the U.S. industry leader develop its Z-40, -46, -48, and Z-50 wind turbines, which ranged from 550 kW–750 kW in size. In 2000, NREL won another R&D 100 Award for its NorthWind 100/20 wind turbine, designed to provide up to 100 kW of electricity, especially for remote, off-grid, extreme-cold locations. The NWTC’s strategy was to continue to help these smaller technology companies in the hopes that the General Electrics (GEs) and Siemens of the world would soon throw their hats in the ring.

All was not smooth sailing for the wind industry at the turn of the millennium. With fossil fuels at their cheapest, many American wind companies filed for bankruptcy. Industry-leading Kenentech—a subsidiary of U.S. Windpower—made a huge bet on its variable-speed 33M-VS turbine, which was not adequately tested and thus riddled with failures. The company filed for bankruptcy, and wind farms were increasingly seen as paper tigers, harmful to birds and bugs, offensive to eyes and ears. Inoperable turbines were often left standing—the “angular skeletons” Ulrich Hütter had warned about.

As the tax credits for wind energy lapsed, the domestic market for wind farms was all but destroyed, and only one major company remained in play by 1998: Enron Wind. Meanwhile, Kenentech represented the idealized isolation that often characterizes American innovation—the concept of the lone inventor or sequestered team toiling away for years before suddenly and heroically unveiling a quantum leap forward to an unsuspecting yet thankful public. In reality, the wind energy industry desperately needed increased collaboration rather than competition.

ACT III—Scaling Up

Despite the catastrophic collapse of Kenentech, there was huge value in the variable-speed technology it had championed so heavily. Wind, by its very nature, is an irregular resource with variable speeds. Constant-speed rotors exhibit rising output power as the wind speed increases—to a point—after which, according to an NREL technical report, “the airfoil will stall with increasing wind and consequently lose much of its lift.”[24] Variable-speed technology, first introduced in the mid-1970s, creates a turbine that can “operate constantly at or near its optimum tip-speed ratio [and] … will on average collect up to 10% more annual energy.”[23] The constant output amid fluctuating input also contributes greatly to a more predictable utility grid.

Amid Kenentech’s bankruptcy, Zond had wisely acquired its competitor’s variable-speed innovation. Before it became synonymous with accounting errors and corporate excess, the natural gas and electric power company, Enron, bought Zond and formed Enron Wind. This entity was, in turn, acquired by GE in 2002 after Enron’s collapse.

Learning from the mistakes of Kenentech, GE chose to partner with NREL to incrementally and collaboratively develop the technology at the NWTC. Nationally, new tax credits were awarded to wind farms that produced energy rather than those that just installed turbines, and a new system of Renewable Portfolio Standards (especially in Texas) drove performance improvements across the industry. From 2005 until 2009, installed wind energy capacity grew at a rate of about 40% annually, with much of the boom occurring in Texas.[17]

However, during this same period, the LCOE reversed its downward trend. Having reached a low of around $50/MWh in 2004—approaching cost parity with other forms of nonrenewable energy—the LCOE crept back up toward $90/MWh by 2009.[24] The greatest culprit of this cost increase was a major uptick in gearbox failures. The increasing cost of raw materials, labor, improved manufacturer profitability needs, and turbine upscaling also contributed to rising costs.[24]

Again, NREL took a leadership role in uniting industry and researchers to fix the problem. In 2007, NREL launched its Gearbox Reliability Collaborative (GRC), bringing together representatives from more than 30 companies and organizations.[25] The data gleaned from GRC testing would be made publicly available, a considerable shift from the more secretive and competitive Kenentech approach.[25]

In part because of the success of the GRC, a new era of multimegawatt turbine testing began at the NWTC. NREL's partnership with GE (as well as its Zond predecessor) fostered the commercial production of GE's extremely popular variable-speed 1.5-MW wind turbine—one of which was purchased by DOE and installed at the NWTC for continued research and development. In 2009, the NWTC added a 2.3-MW Siemens turbine, part of a multiyear Cooperative Research and Development Agreement and the largest public-private partnership for wind energy research then undertaken in U.S. history. A year later, the NWTC added yet another utility-scale machine, the Alstom 3-MW ECO 100, which became a long-term part of the GRC study.

As wind turbine performance continued to rise, the LCOE of wind energy again dipped from its most recent peak in the late 2000s. By 2013, the LCOE was back to around $50/MWh, making it competitive with nonrenewable forms of energy.[16] Some states, including Iowa, are now able to produce more than a quarter of their electricity from wind. This trend is expected to continue across the United States in places where wind is a prevalent resource.[26]

Just as a collaborative approach helped in disseminating information and making design improvements, so too a collaborative approach to wind farm siting holds the promise of even greater efficiency and performance.

According to Thresher:

> Today the NREL-developed FAST computer code and other similar "system dynamics" computer codes are used to analyze all of the dynamic loads acting on all of the turbine components, including the tower and the drivetrain loads. … Ongoing research is attempting to compute the interactions between turbines in a wind farm. In particular, this includes wake effects of upstream turbines on downstream turbines. The hope is that we can improve energy capture and reduce loads to improve the overall productivity and cost effectiveness of entire wind farms.[10]

Beginning with NREL's dynamic simulation tools, DOE's Atmosphere to Electrons (A2E) initiative is a multiyear, multilaboratory continuation of collaborative field experiments, specifically aimed at understanding and optimizing the complex physics not only of airflow around a single wind turbine but of entire wind farms. Clearer understanding of fluid flow dynamics can potentially reduce wind farm energy losses by up to 20% and save hundreds of millions of dollars.

This same systems approach—from making a good individual turbine to siting a great, integrated wind farm—is behind the next big frontier of wind energy: offshore wind turbines. Since the late 2000s, NREL has been working with DOE to test and establish international standards for performance, loads, acoustic emissions, and grid integration. In siting these offshore wind farms, multimegawatt turbines of up to 7 MW—or even 10 MW—are theoretically possible, but the harsh marine landscape will present many new challenges, from storms to salt to the particular difficulties of installing such massive machines in the ocean.

Alongside the technical improvements, the latest generation of turbines and wind farms presents a much more pleasing aesthetic on the landscape. From Hütter's feared "angular skeletons," the current breed of multimegawatt machines has evolved into quiet, elegant, and highly efficient wind turbines, presenting streamlined silhouettes and hypnotic movement.

If Don Quixote saw today's wind farms—30 or 40 "giants whirring together in tandem"—he might not be so quick to attack. He might instead dismount his noble steed, take a deep breath, and take comfort in the notion of human ingenuity and collaboration reaching toward a greater understanding and symbiotic relationship with one of the world's most powerful natural forces.

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“We’ll Be Clean When Their Work is Done”
Robert McCall

Chapter 4

Bioenergy

Introduction

On December 16, 1907, thick clouds of black smoke plumed into the winter sky from an armada of battleships, their hulls freshly painted in peacetime white. From the port of Hampton Roads, Virginia, President Theodore Roosevelt was deploying a sample of the powerful U.S. naval force, soon known as the Great White Fleet. The 14-month circumnavigation of the globe would serve as a solid example of his foreign policy ideology to “speak softly and carry a big stick.”

Coal was the sole power source and fueling this fleet with “black diamonds” was a core challenge of the voyage. Each ship’s 2,000-ton capacity had to be replenished every two weeks in a foreign port. This took several days of back-breaking labor, after which “the crew would spend several more days cleaning the ship, inside and out, fore and aft, since coal dust settled everywhere.”[1]

In October 1908, the same month the Great White Fleet reached Japan, Henry Ford launched his Model T, an affordable machine primed to define an industry and forever change the nature of American transportation. Though the automobile is now synonymous with oil consumption, Ford’s Model T was hardly a gas guzzler—in fact, it could run on gasoline, kerosene, ethanol, and other alcohol fuels.

The concept of fuel choice eluded most motorists throughout the 20th century, to say nothing of other larger-scale fuel consumers. In 2009, Secretary of the Navy Ray Mabus announced a series of sweeping energy goals aimed at reducing dependence on foreign oil while increasing alternative energy use. Among these specific objectives was for the U.S. Navy to deploy a “Great Green Fleet” by 2016. With biomass being the primary energy source capable of producing high quantities of transportation fuels, the development of bioenergy was slated to play a key role in the next era of military combat.

But was the technology ready?

At the center of this push to develop bioenergy well beyond its rudimentary origins to the level of military-grade performance was the National Renewable Energy Laboratory (NREL).

ACT I—Fuel of the Future

After building a plant to produce methanol (wood alcohol)—an extremely clean-burning fuel—Henry Ford maintained his faith in biofuels well into the Roaring Twenties. According to a 1925 *New York Times* article, Ford claimed:

> The fuel of the future … is going to come from fruit, like that sumac out by the road, or from apples, weeds, sawdust—almost anything. There is fuel in every bit of vegetable matter that can be fermented. There's enough alcohol in one year's yield of an acre of potatoes to drive the machinery necessary to cultivate the field for a hundred years.[2]

Ford may have been speaking to his hopes for future adoption of biofuels, but the technology was hardly new or untested in the 1920s. Alcohol fuel had been used at least a hundred years before Ford spoke to the *Times*, notably in Samuel Morey's internal combustion engine prototype in 1826.[3] Alcohol was long used for illumination as well as transportation, and an 1834 patent for an alcohol lamp fuel helped alcohol fuels displace whale oil and vegetable oil as typical power sources for light. When petroleum arrived on the scene in the 1860s, it was reasonably competitive with these biofuels, but to help pay for the Civil War, an exorbitant tax was placed on alcohol, making petroleum-based kerosene the cost-effective fuel choice thereafter. The Oil Age began.[3]

However, when the horseless carriage industry got rolling in the 1890s, the preferred type of fuel was very much up for debate. In 1892, Rudolph Diesel patented his highly efficient namesake engine, which he modified to run on peanut oil. Thousands of tests conducted by the U.S. Department of Agriculture, U.S. Navy, and the U.S. Geological Survey in the early 1900s concluded that alcohol was not only efficient but also a cleaner fuel choice compared to kerosene or gasoline.[4]

Gasoline, however, was a force to be reckoned with. Refining crude oil and selling the gasoline byproduct was lucrative from the outset. No one capitalized on the opportunity more than John D. Rockefeller. In 1862, he formed Standard Oil and realized he could create more market stability by consolidating companies and moving toward vertical integration. Rockefeller soon controlled the refining process as well as the transportation of oil and its sale at retail outlets (i.e., gas stations). By the 1880s, he controlled 80%–90% of the oil market, and by the turn of the century his control reached full monopoly status, making him the richest man in America.

Beginning in 1902, Ida Tarbell's series of articles that later became the book *The History of the Standard Oil Company* (1904) vilified the oil magnate, and Theodore Roosevelt soon led the antitrust charge against Standard Oil. In 1906, Rockefeller's monopoly was broken into about 20 subsidiaries (including the resulting "Seven Sisters"—what became Exxon, Mobil, Chevron, Gulf, Texaco, BP, and Shell). Roosevelt lifted the Civil War-era alcohol tax, making ethanol once again competitive with gasoline, and it appeared that alcohol fuel would see a resurgence. But Rockefeller used his considerable political influence to persuade Congress to pass the 18th Amendment in 1919, ushering in the era of Prohibition and another hiatus for the development of alcohol fuels. It took the Great Depression and its devastating toll on agricultural commodity prices to make ethanol an attractive option for farm relief.

Ford grew up on a farm and was a champion of agrarian culture, despite the lasting impression of him as a catalyst for urbanization and industry. He knew that alcohol fuel could be produced from a wide variety of farm products or byproducts. He also believed that a mutual dependence between American agriculture and industry was a win-win situation. "If we industrialists want the American farmer to be our customer," Ford once said, "we must find a way to become his customer."[5]

The idea of finding new markets for agricultural products and byproducts became known as "farm chemurgy," and Ford sponsored a 1935 conference on the topic in Dearborn, Michigan, with others following annually. Unfortunately, crop failures in the late 1930s and the start of World War II shifted the focus of agricultural production back to food needs, and by the postwar period, the gasoline industry and infrastructure were too powerful and entrenched to make alternative fuels compelling. It would take the gas crisis of the 1970s for interest in biofuels to return.

By 1972, most research of biofuel processes was consolidated into the National Science Foundation's Research Applied to National Needs (RANN) program. Under RANN, the Solar Energy Panel was formed to study renewable energy possibilities, an effort that included the Fuels From Biomass (FFB) branch. FFB was further subdivided into projects focused on agricultural residue, terrestrial and marine biomass production and conversion, and advanced research and development.[6] In the wake of the 1973 oil crisis, national research and outreach efforts quickly intensified around bioenergy as well as other renewable energy sources, such as solar and wind energy. While much of the focus on biomass was for transportation fuel, replacing or supplementing residential heating oil with wood stoves was one simple, early success—the number of woodstoves used nationwide increased from about 160,000 in 1972 to about 1 million by 1980.

Stoves were only a start. The cultivation of bioenergy on a mass scale entails converting biomass into fuels and other valuable chemicals through more sophisticated biochemical or thermochemical processes—either fermenting a biomass feedstock with biological catalysts or introducing heat to produce a liquid or gas biofuel.

Federal energy initiatives were consolidated at the cabinet level under the newly formed Department of Energy (DOE), and the Solar Energy Research Institute (SERI) commenced operations on July 5, 1977. SERI's primary objective was to develop solar photovoltaic technology, but because biomass research and development (R&D) had direct applications as a replacement for liquid transportation fuels, it was an appealing area for further study. Within SERI's first year, the institute began work on a thermochemical gasifier, and "a comprehensive assessment was made of biomass availability for energy production on a large scale."[7]

In the meantime, the DOE had formed a far-reaching biofuels program, a component of which was the Aquatic Species Program (ASP), launched at SERI in 1978. The ASP initially focused on producing hydrogen from algae, but by 1980 the intent shifted to studying the potential for algae to produce biodiesel and other transportation fuels.[8] Further expansion of early R&D included studying algal photosynthesis, as well as cultivation, conversion, and genetic engineering, and building a living library of algal species. With more than 100,000 known species of algae, collecting these strains was a daunting yet promising task. According to energy expert Daniel Yergin:

> Algae are little refineries; they absorb sunlight and CO_2 and produce oxygen (about 40% of the world's supply) and bio-oils. Those oils are, in molecular terms, very suitable for the production of gasoline and diesel and jet fuel. They are also, theoretically, very efficient.… One basic challenge in all the algae work is to find the most productive strains of algae and then maintain the stability of the algae population—which has proved very challenging—and do all this at commercial scale.[5]

As the ASP got underway at SERI, the Energy Security Act provided another boost for biofuels, introducing a federal ethanol tax credit of up to $0.60 per gallon for businesses that sold or used biofuels. The 1980 legislation also provided financial assistance—primarily loan guarantees—for alcohol fuel plants (one of the resulting pilot plants successfully restructured its loan and still operates today, producing 80 million gallons of alcohol fuel per year). By the early 1980s, small biomass plants operated in California and Maine, typically using sawdust as their feedstock.[9]

> “Within SERI's first year, the institute began work on a thermochemical gasifier, and a comprehensive assessment was made of biomass availability for energy production on a large scale.”

Back at SERI, 1982 was a milestone year. The young institute won its first R&D 100 Award for researcher Tom Reed's High Pressure Oxygen Downdraft Gasifier, which turned wood and waste into synthetic gas (syngas) that could be further processed into different hydrocarbons—the same chemical compounds released by many fossil fuels. An early example of biomass technology transfer, Reed's prototype was soon commercialized—by 1987, industry partner Syn-Gas Inc. had scaled up to produce 75 tons of syngas per day.[10] The ASP, meanwhile, had collected more than 3,000 strains of algae and developed an in-depth understanding of how to manipulate various bioenergy conversion processes. Chemist Paul Roessler's efforts to isolate a key enzyme in lipid biosynthesis, for instance, provided a vital building block for later efforts to manipulate microalgal lipids through genetic engineering.[8]

With multiple R&D programs under way, SERI was on the biomass map as a leader in conversion technology. Bioenergy was finally moving forward.

ACT II—Creation of the National Bioenergy Center

Despite this stake in the ground, fluctuating government commitment and overt challenges from the oil and auto industries proved to be formidable. The Reagan-era funding cuts took their toll on all SERI programs, but in 1988, the Alternative Motor Fuels Act followed on the Energy Security Act, supporting further R&D while providing fuel economy credits to car manufacturers. Unfortunately, federal production tax credits did not have the same effect on the bioenergy industry as they did on other renewables, and overproduction of oil in the Arab world sent the price of crude oil plummeting during the mid- to late-1980s. The result was a decrease in alternative fuels interest. When the Gulf War commenced in 1990 and oil prices spiked, the interest returned. This pattern of knee-jerk reactions to oil prices and on-again-off-again commitment to renewables would have long-term effects on the evolution of bioenergy.

Shortly after President George H. W. Bush elevated SERI to national laboratory status in 1991, the newly named National Renewable Energy Laboratory officially broadened its mission and added the Alternative Fuels Data Center (AFDC) and Alternative Fuels Research and Development Program (AFRD) to its roster:

The AFDC, which is a database, supports the Alternative Motor Fuels Act demonstration efforts by acting as a repository for information on alternative-fuel vehicle reliability, performance, and operating costs. The center also supplies modern database management software and statistical software to users. The AFRD carries out research on alternative fuels. Researchers evaluate the merits of various fuels (often using AFDC data) to identify and fulfill research needs.[11]

These programs were initially without a physical home on campus, a situation remedied in 1994 with the completion of the Alternative Fuels User Facility, which provided labs for methanol and ethanol production as well as space for industry partners to evaluate alternative biofuels.[12] This user facility joined the Thermochemical User Facility, housed in NREL's Field Test Laboratory Building, which let scientists undertake the typically expensive and risky testing phase of new feedstocks and conversion processes in a highly cost-effective manner.

As a result of this concerted effort, the first half of the 1990s brought numerous accolades for NREL's bioenergy R&D, in both thermochemical and biochemical conversion pathways. Helena Chum's research team landed an R&D 100 Award in 1990 for its Vortex Pyrolysis Reactor and the associated thermochemical process that quickly and inexpensively converted wood biomass into a replacement for petroleum-derived phenol. Phenol is an essential substance for making plastics, glues, fuels, and chemicals, so the potential applications of Chum's thermochemical innovation were limitless.

Another R&D 100 Award came in 1993 for NREL's Ethanol from Corn Fiber process, a biochemical approach that used enzymes to ferment carbs from corn fibers into ethanol. Two years later, NREL was again recognized for its role in developing Zymomonas, a metabolically engineered catalyst enabling the efficient conversion of wood, grass, waste, and other cellulose material into ethanol. Meanwhile, on a national scale, biomass was also being used more and more for power and heat generation. By 1996, about 7,000 MW of biomass-based electricity generation were on the grid, led by California.

Despite these innovations, the bioenergy industry hit a massive speed bump in the mid-1990s, with California particularly battered by the downturn. A quarter of the state's alternative energy plants shut down with the passage of the Electric Utility Industry Restructuring Act, which created a commodity market for electricity producers and was intended to foster competition. In reality, increased demand for power amid deregulation allowed unscrupulous energy companies to raise prices to unprecedented levels. California was soon dealing with bankrupt utilities, rolling blackouts, and a full-scale energy crisis.[13]

Throughout this crisis of the late 1990s, annual domestic ethanol production had stalled at about 1.5 billion gallons in 1999—not much more than its 1993 production—and biomass used for power generation also increased at a snail's pace. With the price of crude oil under $20 per barrel, in 1995 DOE funding for the ASP program had dried up in favor of new ethanol funding—the alternative energy equivalent of "robbing Peter to pay Paul." Only a few hundred of the more than 3,000 algal strains collected by the ASP were sent to the University of Hawaii for archiving.

The ASP closeout report, published in July 1998, became a critical document linking past with the future, with the candid words of its Executive Summary proving highly prophetic: "When the time is right, we fully expect to see renewed interest in algae as a source of fuels and other chemicals. The highlights presented here should serve as a foundation for these future efforts."[8]

Meanwhile, as the price of crude oil crept back up, the federal government extended its tax exemptions for ethanol-blended fuels. That same year, 1998, NREL won an R&D 100 Award for its "Vermont" High-Throughput Gasifier, which turned wood chips into clean-burning gas to fuel an unmodified gas turbine. The first-of-its-kind system enabled biomass conversion at a scale of 200 tons of biomass per day and could "nearly double the electricity-generating efficiency typical of today's biopower industry."[14] Another award came in 2000 for Real-Time Biomass Analysis, a portable system designed to help the forestry and paper industries analyze the chemical and mechanical properties of wood and determine optimal harvest and use.

Renewed funding at NREL allowed for the creation of the National Bioenergy Center (NBC) in October 2000. Led by NREL, this collaborative consortium of other DOE laboratories took on a specific mission: make cellulosic ethanol cost-competitive with gasoline by 2012. It was no small task.

In 2000, the ethanol industry still only produced about 1.6 billion gallons per year. According to the May 2000 issue of the Alternative Fuel Price Report, the adjusted price of ethanol (E85) per gallon was $1.80, compared to $1.52 per gallon of gasoline.[15] (Note: this price is adjusted to reflect that the energy in ethanol is only equivalent to about two-thirds the energy in gasoline.) NREL's NBC would have to "demonstrate a modeled, cost-competitive, biochemically derived ethanol price ($1.33–$1.49/gallon) by 2012."[16]

In 2000, Congress formed the Biomass Research and Development Board to support the collaborative multilaboratory projects undertaken by the NBC, among other federal agencies. The board developed a plan to analyze and better organize the biofuels supply chain—from initial feedstock production through conversion and end-use—and outlined the three generations of biofuels:

The first generation includes corn for ethanol and soybeans for biodiesel. These are the types of biofuels that are being most second-guessed currently for their efficiency and environmental value. The second generation of biofuels reflects the concerns articulated about corn and soy. This next generation includes plant parts, such as stems and husks, and demonstrates a need for more cellulosic conversion technology. The third generation includes algae and grasses. While more research and development is necessary before these biofuels can be commercialized, they promise to offer more energy efficiency and less threat to food prices.[17]

The debate over first-generation biofuels became a hot topic in the 2000s, with adversaries battling it out over whether the direct and indirect costs of producing biofuels outweighed the energy provided. Often oversimplified as the "food versus fuel" ultimatum, the question is whether too much food crop—corn, for instance—is being used to produce ethanol versus edible sustenance; thus, adversely affecting the price of food. Furthermore, it examines how much time, money, and other forms of energy go into the production of ethanol. Answering these questions became another core area of NREL analysis.

Part of this answer came in the form of second-generation cellulosic ethanol research and development. For a start, cellulosic ethanol typically uses either harvested plant material indigestible to humans (such as corn husks) or discarded byproducts of food harvesting (such as corn stalks) usually left to decompose on agricultural lands. These "leftovers" are therefore not part of the "food versus fuel" debate and would otherwise simply add to our waste production or, if left to rot, add to our existing greenhouse gases.

About "85% of the residue left over after grain harvest (stover) rots on the ground, releasing CO_2," so collecting and repurposing this stover has a beneficial environmental impact well beyond its potential use as a biofuel feedstock.18 In 2002, NREL undertook "a comprehensive accounting of a product's flows to and from the environment" of corn-stover-based ethanol versus petroleum—the first study of its kind.[18]

Nevertheless, and true to pattern, the early 2000s saw another slowdown in biomass support and production, with power generation declining between 2000 and 2002. Funding was further pulled from the remnant ASP archive in Hawaii, with only 100 to 150 algal strains left from the more than 3,000 initially collected. And the United States still lagged in its ability to produce ethanol—less than 3 billion gallons in 2003—while in other parts of the world, production and use of alternative fuels was growing exponentially. Now, the unquestioned leader in bioenergy was Brazil.[16]

In the 1970s, Brazil was unable to produce or import petroleum on the scale required, so it turned to its major cash crop, sugarcane, as an alternative fuel source. Due in part to government subsidies and legislation in Brazil, the 1980s and 1990s brought a massive increase in ethanol production and retailing as well as manufacturing flex-fuel automobiles:

[Flex-fuel autos] are vehicles with onboard computers that can detect by 'sniffing'—that is, sensing whether the fuel is gasoline, a mixture of gasoline and ethanol, or mostly ethanol—and then adjust the engine accordingly.… In 2003, about 40,000 flex-fuel cars were sold in Brazil. By 2008, this number had surged to just over two million, and flex-fuel constituted about 94% of all new cars sold in Brazil. This means that the motorist at the pump can decide what is cheaper on any given day and put that fuel into the engine.[5]

With consistent research, as well as support from government and industry, Brazil achieved the impossible and became energy independent. While U.S. energy needs were and are vastly greater than those of Brazil, the model for biofuels-based self-sufficiency had been tested and succeeded on a national scale. It was up to America to catch up.

ACT III—NREL Welcomes a President

In 2004, 10 years after the United States started manufacturing flex-fuel cars, President George W. Bush got the ethanol bug. After the public-relations firestorm of Hurricane Katrina, he called for an end to America's addiction to oil. Ethanol refineries sprang up all over the American Midwest, providing jobs as well as much-needed biofuels. By 2007, annual domestic ethanol production would surge to more than 6.5 billion gallons.

But there was plenty more untapped bioenergy potential beyond corn-based ethanol. In 2005, Oak Ridge National Laboratory (ORNL), one of NREL's key partners, completed its soon-to-be-famous "Billion-Ton Study," which concluded that the United States had the ability to produce up to 1.3 billion tons of biomass feedstock annually without a negative impact on food production capabilities. The report aimed to put an end to the food-versus-fuel debate once and for all. (ORNL produced a corroborating "Billion-Ton Update" in 2011 that reached the same conclusion while adding more comprehensive cost and land-use analyses.)[19]

The study took into account the fact that many potential cellulosic biofuel plants are "able to grow on marginal soils not suited for traditional agriculture," drastically increasing the amount of soil that can be cultivated for cellulosic ethanol purposes.[17] However, it also placed a rough limit on the national capacity to produce cellulosic ethanol, capping the "resource potential sufficient to displace more than 30% of U.S. 2004 finished motor gasoline demand."[20] Thus, while cellulosic ethanol was certainly one vital avenue toward displacing gasoline, additional feedstocks and conversion processes were still needed to achieve energy independence.

Welcome back, algal biofuels.

Algae, a type of cellulosic biomass (plants deemed inedible by humans), was another prevalent potential source of energy outside the food-versus-fuel debate. Those familiar with the ASP and its findings knew that algal biofuels could help the United States achieve true energy independence. In 2005, the first car had been developed that could run on algal biodiesel, and a barrel of this biofuel was produced in a California backyard distillery that year. In 2007, the NBC launched a strategic initiative on algal biofuels that outlined a strategy for multiple commercial partnerships, including a Cooperative Research and Development Agreement with Chevron. More than 30 algal biofuel companies could feasibly contribute to the effort.[21] The long-dormant ASP had, in essence, been resurrected.

Meanwhile, in 2006, President Bush became only the second sitting president to visit NREL, touring biomass facilities on campus and watching a general demonstration of the cellulosic ethanol conversion process. That same year, DOE's Advanced Energy Initiative again challenged NREL to create an affordable transportation fuel by 2012.[22] Renewable Fuels Standards passed by Congress in 2007 called for 35 billion gallons of alternative biofuels by 2022. A new biofuels boom promptly began nationwide. Back on campus, NREL's Renewable Fuels Heating Plant, completed the same year, burned wood waste to heat the Colorado campus, saving about $400,000 in natural gas costs during its first year of operation.

Then, a new crisis hit home.

On July 11, 2008, crude oil prices peaked at $147 per barrel. By September, the economy came crumbling down. But this time, the renewable energy industry was primed to step up—the United States was now producing more than 9 billion gallons of ethanol per year and next-generation, commercial-scale cellulosic ethanol plants were finally becoming a reality.

In late 2009, DuPont began operating one of the world's first pilot-scale commercial ethanol plants in Vonore, Tennessee. The 74,000-square-foot plant was the culmination of a partnership between DuPont and NREL that began in 2002, based on DOE funding for partnerships with national laboratories on cellulosic ethanol research and development.

NREL helped DuPont develop a new, ammonia-based pretreatment approach, then retrofitting DuPont's reactors, while sharing with DuPont its recent discoveries with the Z. mobilis bacteria enzyme. NREL also provided economic modeling for the cellulosic ethanol process to help ensure commercial profitability.

"When companies like DuPont sink millions of dollars into a project, it is important they get it right the first time," said NREL Biochemical Conversion Manager Rick Elander.[23]

To help ensure successful tech transfer and commercialization, the American Reinvestment and Recovery Act of 2009 included an Alternative Fuel Vehicles Pilot Program. This, in turn, provided funds for the National Advanced Biofuels Consortium, aimed at quickly moving basic research to applied, industrial-scale technology. The consortium included members from industry, national laboratories, and university research, and was to be led by NREL.

This post-economic-downturn period marked a renaissance in algal biofuels. In 2008, NREL issued its first Laboratory Directed Research and Development (LDRD) grant to one of the NBC's algal biofuels projects. Seven more algal biofuels projects won LDRDs between 2009 and 2011.[24] After holding its first National Algal Biofuels Workshop in 2008—organized in part by NREL's Al Darzins and Phil Pienkos—DOE published its official "roadmap" in May 2010, drawing on the earlier work of the ASP as "one of the most comprehensive research efforts to date on fuels from microalgae," and laying out the challenges of creating biofuels from algae in this new era.[25]

As much as any renewable energy technology, the story of the biomass industry over the past 40 years has been one of fluctuating funding and federal support, especially in regard to experimental programs like those supporting algal biofuels research and development. In 2010, DOE established the Algal Feedstock program to create consistent long-term funding at NREL and other national laboratories—a huge step in the right direction.

NREL made its own huge steps when it announced in 2012 that it had stepped up to the Alternative Energy Initiative's cost challenge and succeeded. Moreover, researchers achieved affordability of cellulosic ethanol "using two separate conversion platforms: biochemical and thermochemical. The biochemical process can produce ethanol at a minimum ethanol selling price of $2.15/gallon. The thermochemical platform demonstrated a minimum ethanol selling price of $2.05/gallon."[26] It was clear that both conversion pathways held tremendous value.

Today, NREL is poised to help industry move beyond corn-based ethanol to second-generation (cellulosic) and third-generation (algal and grasses) technologies. In 2015, President Barack Obama's far-reaching Clean Power Plan provided support for commercializing algae-based technologies that convert power plant CO_2 into fuels, feeds, fertilizers, and other valuable products, including jet fuel.

While NREL's biofuels mission has focused on displacing oil in the transportation sector, recent commercial and military proponents increasingly point to the mainstreaming of bioenergy. The Navy's "Great Green Fleet" demonstration was preceded in July 2012 with an interim demonstration during the Rim of the Pacific, "the world's largest maritime exercise." Five naval ships and their aircraft were powered by "drop-in replacement" biofuel blends—50/50 mixtures of used cooking oil and algae, along with more traditional petroleum-based marine diesel or jet fuel. The 2012 demonstration was an unqualified success and, as a result, the Navy launched a concurrent Aircraft Energy Conservation Program to revamp the fuel paradigm for its nearly 4,000 aircraft.[27] As of this writing, plans were underway to deploy the full armada in 2016 and, according to Secretary of the Navy Ray Mabus, "The Great Green Fleet will signal to the world America's continued naval supremacy, unleashed from the tether of foreign oil."[27]

Marine and jet fuel represent a vital subsection of transportation fuels, but NREL is focusing on next-generation "drop-in" hydrocarbon fuels. While most existing biofuels require remodeling or retrofitting and other modifications to refineries, gas stations, and vehicles, the value of drop-in biofuels is that they can function within the existing transportation industry infrastructure and could instantly replace gasoline, diesel, or jet fuel. A 2015 NREL-led study is determining which biomass-based oxygenates and processes can be tolerated and eventually meet the quality standards of existing diesel and gasoline engines.[28]

Meanwhile, with help from NREL, commercial-scale cellulosic ethanol facilities are finally a reality. In September 2014, POET's Project Liberty facility opened in Emmetsburg, Iowa, projected to produce 20 million gallons of cellulosic ethanol per year. Adding an estimated 25 million gallons to this annual estimate, Abengoa's biomass facility opened a month later in Kansas. And in October 2015, DuPont took the next huge step in biofuels production, opening the world's largest cellulosic ethanol facility in Nevada, Iowa, expected to produce 30 million gallons of cellulosic ethanol per year.

> "In 2006, President Bush became only the second sitting president to visit NREL, touring biomass facilities on campus and watching a general demonstation of the cellulosic ethanol conversion process."

Built upon the foundations of more than 10 joint DuPont-NREL U.S. patents in biomass pretreatment and production, biorefineries like DuPont's also improve the rural region's economy, providing employment for more than 1,000 people and obtaining corn stover from about 500 farmers.[29]

On water, in the sky, and across the roads and agricultural fields of America, biofuels are now here to stay.

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"Perfect Weather for a Streamlined World"
Robert McCall

Chapter 5

Changing the Built Environment–Our Evolving Campus

Introduction

The classic example is a lizard in the desert, hunkering under a rock during a hot day, then climbing on top of this same rock at night, enjoying the heat the rock absorbed in the afternoon. The concept of passive solar is deceptively simple: employ the right materials, position them the right way, and let the sun do its job.

On May 18–19, 1976, at the University of New Mexico, "solar energy's 'lunatic fringe' and assorted hippies, architects, engineers, national laboratory scientists, and bureaucrats finally came together to exchange information and learn more about the ascendant solar technology for heating and cooling buildings."[1] The Passive Solar Heating and Cooling Conference was the first of its kind and served as an inflection point: After 1976, the number of passive solar homes in the United States grew exponentially.

Of course, passive solar was only one of many building technologies gaining traction, with researchers, builders, companies, and consumers increasingly exploring photovoltaics, wind, biomass, hydrogen, and geothermal technologies as means of generating and conserving energy for homes and commercial structures. At the center of this uptick in renewable energy interest was a laboratory without a home.

It took two years of competitive bidding before the nascent laboratory originally known as the Solar Energy Research Institute (SERI) found its home base. In the decades that followed, SERI evolved into the National Renewable Energy Laboratory (NREL), which not only built a permanent campus but also pioneered a series of principles and technologies that became models for the future of how people live and work together.

ACT I—Roadblocks to Progress

SERI had an unusual architectural beginning. The state of Colorado had donated to the new institute 300 acres of land on the south side of South Table Mountain—previously part of Camp George West, the base for the state's National Guard—but the land would not be officially transferred to SERI until 1982. Years later, an NREL publication joked that when the institute opened, this acreage was "only home to weeds, wildflowers, and rattlesnakes."[2]

In July 1977, inaugural staff members moved into interim facilities in the Denver West Office Park while operating an 11-acre outdoor testing facility largely comprised of trailers. The office park was modified to work as a series of labs. Bob Noun, NREL's executive director of communications and external affairs, remembers the strangeness of doing scientific work in rented and reconfigured office spaces instead of a classic research campus with dedicated laboratory facilities. As important as the research was, the venue didn't quite send the right message of strength and stability. "It was a classic case of the cart before the horse," Noun said. "Congress, in its wisdom, had created this institute to do research on renewable energy, but it did not provide it with the facilities to house all of these incredible scientists and engineers that were being drawn to Golden."[3]

And so, a new, dedicated building was not only important for the researchers themselves, but also for the perception of the laboratory. Construction of a permanent facility would be a sign to the government and to the American people that alternative energy—and the laboratory—were here to stay.

Designs were underway for permanent facilities, including offices and research labs as well as conference, field experiment, library, and visitor facilities. It was hoped that the permanent campus would be a "national showpiece of innovative solar energy design and energy conservation techniques."[4] In other words, SERI intended to walk the talk from the beginning, creating a campus that was itself a working prototype for a new generation of energy-conscious buildings and systems.

Another broader goal was to normalize the technology such that residential and commercial builders would quickly adopt the technology. President Jimmy Carter's 1979 installation of 32 solar thermal panels (used for heating water) on the White House roof showed everyday Americans that solar was a viable option whose time had come. Carter spoke of the small solar array as a crossroads moment: "A generation from now, this solar heater can either be a curiosity, a museum piece, an example of a road not taken, or it can be just a small part of one of the greatest and most exciting adventures ever undertaken by the American people," he said.[5]

In 1978, the U.S. Department of Housing and Urban Development collaborated with SERI and the U.S. Department of Energy (DOE) to initiate the "Passive Residential Design Competition and Demonstration." The newly created SERI's "Passive Technology Branch" was tasked with selecting the winning designs and monitoring them after construction. Ron Judkoff, having arrived in 1978 as the first SERI building scientist, scrambled to write a passive solar design evaluation manual and enlisted the aforementioned "lunatic fringe" solar architects and engineers to choose the approximately 160 winning designs that were then built.[6] Post-construction monitoring showed that these buildings generally performed well in winter, overheated somewhat in summer, and would have been challenging for mainstream builders to replicate in quantity.

Under Director Denis Hayes in 1980, SERI launched the Denver Metro Home Builders Program, hoping to bring the new building technology into common commercial practice. "We got a dozen homebuilders who would agree that if we did the design work and showed them how, without spending any more money, they could have a home that would use far less energy and still be attractive to the general public," Hayes said. "We weren't talking weirdo, hippie communal shelters. It's a home. It just had things deployed differently."[7]

What followed was an impressively publicized "Parade of Homes," with more than 100,000 visitors touring the model houses in the first weekend alone. "People who had been reluctant to be part of this, suddenly started building these things en masse," Hayes said.[7] The two-week event ultimately yielded 31 sales contracts and more than 60 preorders for additional passive solar homes.

However, shortly after he was elected, President Ronald Reagan tried his best to undo what Carter had started, beginning with the physical and rhetorical tactic of removing the solar panels from the White House roof and finishing by slashing SERI funding by more than half.

SERI, undaunted, banded together with the well-funded U.S. military. In 1981, the Military Liaison Office opened at SERI, with seven projects—including the development of passive solar architecture, the use of wind energy for the Department of Defense, and the inauguration of active and passive solar system design workshops for military engineers, architects, and builders—developed in partnership between SERI and the armed forces.

> “A new, dedicated building was not only important for the researchers, but also for the perception of the laboratory. Construction of a permanent facility would be a sign to the government and to the American people that **alternative energy–and the laboratory–were here to stay.**”

The partnership worked and it all but saved SERI. In January 1982, Acting Director Hub Hubbard outlined plans for SERI's future growth—physically as well as conceptually. He pointed out that the $9.5 million federal grant for a laboratory building and field test site showed the government's faith in SERI. "We have their support," he said.

SERI leaders knew how important it was to demonstrate to the American people—and others watching around the world—that regardless of who resided at 1600 Pennsylvania Avenue, SERI would keep doing the work necessary to bring about a new energy paradigm.

ACT II—Breaking Ground

Shovel hit dirt for that first permanent building, the Field Test Laboratory Building (FTLB), in July 1982. It had been in the works for years; in 1978, a SERI publication described the recently conceptualized project as a "national showpiece of innovative solar energy design and energy conservation techniques" that would "complement the special environmental and geographic features of the site."[4] However, the development had the potential to transform the rolling Colorado landscape that surrounded Golden. Conscious of the fact that citizens might balk at the changes, SERI wrote an open letter, addressed only to "Dear neighbor," in which Public Affairs Manager B. F. Velazquez outlined the plan for this 70,000-square-foot laboratory building. He described work at the lab as nonpolluting and noiseless, and proclaimed that it would "result in significant renewable energy advances as our country strives to break away from dependence on foreign oil."

The building, which opened in 1983, was designed as a series of blocks, housing high-bay laboratories for biotech research and assembly areas for outdoor experiments. The look was futuristic and crisp, a clear signal that the development of solar power was truly at the cutting edge of technological innovation. SERI, long troubled by financial setbacks, finally had the opportunity to prove that the organization had not only survived but was also ready for a bright future.

By June 1983, construction was 70% complete. *SERIscope,* an internal newsletter for the lab, printed a cover story explaining that the low-slung design and muted color would have "a minimum impact upon the eye of the observer."[8] Skylights would let light and heat into the building, and a massive glass front would also provide passive solar heat and ample daylighting.

Inside, the designers wanted open access via what the article called a "high-technology, exposed style," showing the pipes, ducts, and other "guts" of the building.[8] The highlight, more than anything else, was flexibility: Most of the building was open, construction-ready space, ready to be configured to meet the next research need. In keeping with that flexibility was the Energy Monitoring and Control System, an early iteration of smart building technology that kept an electronic eye on the structure's energy use and provided warnings should any systems need a tune-up. Electronically collecting this kind of data over time allowed the building to serve as a living laboratory, providing necessary quantitative information for research papers.

It didn't take long, however, for SERI leaders to realize that the campus needed to grow and further improve the efficiency of its buildings. While passive solar was a major theme in energy-efficient residential architecture at the time, Ron Judkoff, a pioneer of SERI's Buildings Research Program, describes that in applying the same principles to a lab like the FTLB, "any of us that were Building Energy scientists knew that building was going to overheat. The load profile in a laboratory building is extremely different from the load profile in a residence."[9] Furthermore, the FTLB could not house the additional lab space needed by the expanding scientific staff and, in late 1984, conceptual design got underway for a second permanent building to be added just east of the FTLB.[10]

This new Solar Energy Research Facility (SERF) was designed with the ability to foster the work of 250 employees and 53,000 square feet of both dry labs (filled with computers and analysts) and wet labs (filled with chemicals, biological agents, and scientific experimentation stations).[10] The SERF was also the first building project on campus in which SERI Building Energy Scientists were formal and active participants in the design process, led by Judkoff and Roland Hulstrom, one of SERI's solar photovoltaics (PV) experts. SERI worked with Anderson, DeBartolo, and Pan, an architectural and engineering firm, on an energy design process in which software simulations were used to guide many of the energy-related design decisions. The process established a new paradigm for ultra-efficient building design on the NREL campus and elsewhere.

A January 1985 *SERIscope* article announced the beginning of Phase B, designing the SERF; outlined Phase C, adding permanent offices to replace Denver West Buildings 15 and 17; and introduced Phase D, adding additional employee and guest facilities.[10] The SERI campus was no longer just a collection of makeshift labs. SERI was becoming a community—one that needed an on-site cafeteria; an auditorium so that researchers from disparate fields could share information with colleagues and host collaborative workshops; and a visitor's center, so the interested public could learn about the world-changing science being done in this little pocket of the Rockies.

In 1991, President George H. W. Bush elevated SERI to the status of a national laboratory and changed its name to the National Renewable Energy Laboratory.[11] The name change resulted in a budget increase and gave Associate Director Jerry Bellows and his team the sense that they could build more facilities, that they were finally on stable ground.[12] The change also freed the lab to seek capital funding, which could be used for physical expansion as well as major laboratory instruments.

Bellows, who worked alongside Director Richard Truly, oversaw capital budgeting to see if the lab could really get the additional new facilities it needed. After developing a concept for private financing, Bellows and his team came up against the DOE's reluctance to accept third-party funding. However, DOE supported the idea of a new permanent building, soon to be known as the Science & Technology Facility (S&TF) and began working with NREL to allocate the necessary federal funds.[12]

In the meantime, the SERF opened in 1993. Housing 42 separate laboratories, all dedicated to research on photovoltaics, superconductivity, and associated material science, the structure would prove to be one of the government's most energy efficient buildings, using about 40% less energy than typical research facilities.[2] Characteristic of the organization's advocacy of solar and other forms of alternative energy, the building is perfectly sited to make the most of the available Colorado sunlight. Offices and hallways are lit naturally as much as possible. In true NREL integrative fashion, less artificial light meant less heat produced, which makes cooling costs—both economic and energetic—far lower than in typical buildings.13 The SERF also became an early model for the Federal Energy Management Program's Labs 21 Project, "a 'whole building' approach to designing low-energy, high-performance laboratories."[14]

This approach was equally valid for the design of the more public-facing 6,400-square-foot Visitors Center (VC), completed in 1994. The most obvious architectural innovation was its undulating Trombe wall, used to increase the lighting and heating efficiency of the building:

The south-facing wall has five sections, each angled in a "V" shape. Windows on the southeast side of the "V" provide natural daylighting and early morning heat. Facing south and southwest are thick concrete walls coated with black paint and faced with glass. A small airspace separates the wall from the glass. Direct solar radiation is absorbed by the wall, trapped by the glass, and conducted inward to gradually heat the exhibit hall later in the day.[15]

With lighting technologies changing rapidly in the mid-1990s, the VC also became a test bed and demonstration opportunity for new lighting technologies, including a range of compact fluorescent lamp (CFL) and T-8 fluorescent technologies. Later, the VC housed innovative equipment for mixing evaporative cooling with traditional heating, ventilation, and air conditioning (HVAC) equipment and was one of the first buildings on campus to be metered in order to better understand where energy was going on campus.[16]

In 1994, wind energy pioneer Robert Thresher prepared a document for the DOE that outlined his plans for upgrading the National Wind Technology Center, which occupies 305 acres north of Golden. The move was a continuation of the absorption of a small part of the Rocky Flats Plant into SERI and then NREL, and Thresher now focused on the construction of a 10,000-square-foot Industrial User Facility. Thresher wanted the new wind center to include an advanced research wind turbine facility, with space for two side-by-side test machines that could gauge subtle differences in the performance of wind turbines.[17] The National Wind Technology Center investment cemented NREL's identity as a renewable energy powerhouse with an evolving mission beyond solar photovoltaics.

Back at NREL's South Table Mountain campus, and completed in 1996 with heavy input from Buildings Energy researchers, such as Paul Torcellini, the Thermal Test Facility (TTF) was another example of approaching a 10,000-square-foot facility—a typical size for commercial buildings—in an innovative way. The open-space, high-bay TTF labs were dedicated to testing energy-saving technologies, so it made sense that the building itself was state of the art from an energy efficiency point of view.[2] Window overhangs kept direct sunlight out during the hot summer months, while computer simulations helped designers settle on window sizes that allowed for the right balance of daylighting and heat transfer. Daylight from special clerestory windows—designed to reduce heat flow—along with energy efficient lighting—including CFLs, T-8s, and motion sensors—helped reduce light-based energy use by 75%.[18] The TTF served as a bridge between laboratories and commercial buildings and led the way for aggressive energy efficiency of over 50% savings from baselines.

In 1997, *Inside NREL*, a newsletter that had replaced *Seriscope*, published two photographs on the front page. "Then" was a small inset that showed the site in 1977—rolling land, a single road, and a few scattered buildings, mostly on the very bottom edge of the picture. "Now" was a futuristic landscape with cleanly articulated roads leading to state-of-the-art buildings, including the Alternative Fuels User Facility, the Solar Furnace, and to the right, anchoring the image and the campus, the Field Test Laboratory Building rising just barely out of the ground. The Solar Energy Research Facility tripped down the hillside, its facade dominated by a staircase-like array of windows and skylights that could capture and harness the bright Colorado sun.

In 1998, after years of what Bellows called "spikes and valleys, either feast or famine," NREL began to experience a steady upward trend. "In '98 things began to stabilize," he said. "They began to grow, and the trend line tended to be a constant trend line upward."[12]

It was ironic that this laboratory—focused on protecting the environment through developments in renewable energy—had gone through such an unstable period, but in a way, it was a perfect metaphor. Just as the government and citizens were starting to take renewable energy more seriously, NREL's campus came to reflect the stability and forward momentum of the research—first in 1999 when NREL added another 25 acres to its usable space and then, after 2000, beginning a major construction push that brought NREL into its current form.

A 2,600-square-foot Solar Radiation Research Laboratory, housing five laboratories that support optical, electronic, and meteorology functions, was finished in 1999.[2] It proved to be quite a step up from "the mouse-infested [Environmental Protection Agency] EPA sheds" described by scientist Tom Stoffel that were in use until December 1999.

Around this time, graduate student Shanti Pless came to NREL's internship program. One of his earliest tasks was developing a case study evaluation of the 13,600-square-foot Oberlin College Lewis Center for Environmental Studies in Ohio, one of the nation's first attempts at a zero-energy commercial building. This work, along with six other case studies conducted by the Center for Buildings and Thermal Systems, indicated the areas where the leading private-sector firms needed help from NREL to push energy efficiency even further.

Away from the NREL campus, however, a new energy crisis was rearing its head. Beginning in mid-2000 and extending through 2003, spiking energy prices and rolling blackouts plagued millions of residential and commercial customers throughout California. The September 11 attacks in 2001 brought domestic dependence on Middle Eastern oil into the spotlight once again. Perhaps more than any time since the 1970s, major shifts in building and energy-use behaviors would now have to become much more than an experiment. They would become a global necessity.

Act III—A Higher Public Profile

With the cuts of the Reagan administration far in the rearview mirror, the 21st century brought an increased interest among forward-thinking Americans about the importance of renewable energy, a cultural shift that mirrored NREL's coming of age. A 2001 *Associated Press* article described the influx of phone calls fielded by NREL, many from citizens asking how to install solar panels on their houses and corporate representatives inquiring whether wind turbines could help power their businesses.[19] The need for a place like NREL was more palpable than ever.

Campus-wide, the advent of the Sustainable NREL initiative spurred employees to adopt basic energy-saving and water-/waste-minimizing practices in 2002. Meanwhile, NREL researchers Nancy Carlisle and Otto Van Geet were developing their "Laboratories for the 21st Century" case study, analyzing sustainable lab building practices nationwide.

Unfortunately, plans for NREL's forthcoming S&TF were being undertaken without these practices in mind and without close consultation with NREL's Building Energy research experts. Carlisle explained that, as initially designed, the building "was one story, longer than a football field. If we put a building like this on our campus, it would preclude us from being able to develop a pedestrian-based, dense campus."[20] She raised the issue with laboratory director Richard Truly and, in May 2002, undertook a study on how to build the S&TF in a way that was commensurate with

NREL's mission. Though it cost more money, Truly got behind Carlisle's approach and pushed for what became the General Development Vision (GDV)—a set of principles for how to reimagine not only the campus but also the leadership role of NREL.

"While NREL researchers work on exciting alternative energy technologies for the nation, they also believe in 'walking the talk' in their own backyard," wrote Midwest Research Institute President and CEO James L. Spigarelli in the Foreword of the November 2003 GDV report. Truly echoed the sentiment. "Now is the right time to seize the opportunity to clearly establish a vision of the future development of this [campus]," Truly said. "This vision is intended to serve as a model to others as we develop our research campuses to be cutting edge, environmentally sound, and high performing."

As a first step toward this vision, the 71,000-square-foot S&TF was redesigned as a multilevel facility, which engendered a more pedestrian-friendly footprint. The architecture featured a striking conical entryway, modeled after early Native American structures but fashioned in the kind of futuristic metal that would become a basis for the palette of materials campus-wide.

Housing nine advanced materials laboratories, as well as the Process Development and Integration Laboratory, the S&TF improved upon ideas introduced in the earlier SERF lab building and brought many of the conceptual ideas from Carlisle's plan into physical reality. "We'd learned what worked and what didn't work in the SERF," Judkoff said, "and with the S&TF, we got to do it even better."[9] Energy efficient lab ventilation, heat recovery, daylighting, and a major commitment to using sustainable materials made the S&TF a new milestone in commercial building technology. When it opened in 2006, it was designated the first Leadership in Energy and Environmental Design (LEED) Platinum-certified federal facility, 40% more efficient than comparable labs at the time, giving NREL a tremendous amount of notoriety in the field of sustainable commercial building design.[9]

The experiment worked. Now it was time to apply the same thinking and execution to the rest of the campus.

In addition to the architectural design of the structures, NREL took a leadership role in developing intellectual property around both the hardware and software contained in these buildings. Ron Judkoff notched R&D 100 Awards in both fields—in 2005, he won the award for work with NREL's Paul Torcellini and Michael Deru, as well as collaborators from other institutions, on their Targeted Residential Energy Analysis Tools (TREAT) software, a tool enabling building professionals to conduct easier and more accurate energy audits; in 2012, he won another for work with Eric Kozubal, Jason Woods, and Jay Burch on their Desiccant-Enhanced Evaporative Air-Conditioning Cycle, which used 40%–80% less energy than traditional refrigeration-based air conditioners.[21]

In 2008, the Renewable Fuel Heating Plant was completed, which transformed the biomass feedstock of wood chips (about a truckload a day) into hot water for the NREL campus—conceived as a prototype for bioenergy production at similar-sized campuses nationwide.

With the S&TF and biomass heating plants in place, the next step was for NREL to lay out some of the specific nuts and bolts necessary for transforming the South Table Mountain site into a "Campus of the Future." Tangential to this effort, NREL developed a concrete definition of the term "net-zero energy building," and the variations therein, as stated in a 2006 paper coauthored by NREL's Paul Torcellini, Shanti Pless, and Michael Deru.[22]

Known as the Grand Buildout, the next phase began in 2006 under the leadership of Dan Arvizu and extended the vision of sustainable building practices beyond lab buildings to NREL's support and centralized staff facilities—including office spaces, a cafeteria, and a parking garage—that would be relevant to an R&D campus as much as any other commercial or corporate campus. The comprehensive site plan allowed DOE to quickly justify a major capital building program at NREL once the American Recovery and Reinvestment Act was passed in 2008 and federal funds became available. However, DOE issued a clear challenge to NREL, as explained by Integrated Applications Center Director Nancy Carlisle:

> We were told [by DOE's Director of Laboratory Operations Jeff Baker] to "create a new national building performance standard for large-scale commercial buildings that is achievable and marketable now." So, we were told to basically show the world that you can build large-scale net-zero buildings. And we did. We absolutely did.[20]

> "We were told to show the world that you can build large-scale net-zero buildings. And we did. We absolutely did."
>
> – **Nancy Carlisle**, Integrated Applications Center Director

> "On move-in day, when the first wave of 500 occupants entered the RSF, each new resident received a letter from NREL's director, welcoming them to a **game-changing facility** that would eventually win 40 awards for its architecture, construction, engineering, sustainability and technology transfer."

The singular focus of this push was the Research Support Facility (RSF). At several hundred thousand square feet, this would be a giant leap beyond any other attempted net-zero energy building in existence. From the start, Carlisle's team worked alongside Building Energy experts from Judkoff and Torcellini's teams to reimagine the entire design and construction process, searching for a single legal entity that could hire and manage the architect and contractor. Torcellini's team laid out explicit energy-specific performance requirements at the outset of the process, while Carlisle's team integrated the architecture with the campus. Ultimately, the target was to look for a design-build consortium that could provide the most value for a fixed price—the successful bidder would have to commit to as many of the prioritized goals for the building as possible for the money available—hence, the best value.

For the RSF, the best value proposal came from a contractor that committed to providing a building that used half the energy and could provide the remainder of the energy with on-site renewables—a true zero-energy building, the holy grail of energy efficient building. Incremental rewards provided focus for the team as they worked to exceed the high goals that NREL and the contractor established.

"To do this, it takes an integration of the architecture and the engineering," Carlisle said. The siting and footprint of the building had to allow for comprehensive daylighting. Rooftop PV systems required systems integration. Open-ceiling design required workstation planning such that no desk, regardless of its occupant's seniority, would be more than 30 feet from a window, most of them operable; below ground, a concrete "labyrinth" would store thermal energy and allow for passive heating. It all had to come together. Said Judkoff:

> The RSF was a wonderful opportunity because, as an office building, it could serve as a clear replicable example of ultra-efficiency to the many private-sector [architectural and engineering] A&E firms that design office buildings. The floorplates of the building were set at 60 feet wide from north to south, because the light redirecting devices in the south clerestories could project daylight about 45 feet into the space, and the north windows could provide daylight about 15 feet in.

Other major energy saving systems in the building included: a) a hydronic radiant heating and cooling system and an under-floor dedicated outdoor air system to efficiently distribute fresh air, b) evaporative cooling to reduce cooling energy, c) a Solar Transpired Collector Wall to provide free solar heat to the building, d) a system to use the waste heat from the data center to condition the building's fresh air, and e) properly engineered shading devices to minimize unwanted solar gains and glare.

Several of the efficiency technologies used in the building emerged from research done in the NREL Buildings Research Program in collaboration with industry partners. These included the Solar Transpired Collectors on the south façade, the solar tubes in some of the third-floor conference rooms, and the light louvers in the office wings.

Most important of all is the process by which computer simulation was used to both set the energy requirements in the contract specifications and to optimize the energy design of the building by the selected design-build team. Following this process allowed ultra-efficient zero-energy buildings to be designed for sites and climate zones different from those at NREL.[9]

In June 2010, the LEED Platinum RSF opened its doors. It was nothing short of revolutionary. NREL achieved a zero-energy building without spending additional money. This broke two paradigms—one, that buildings must be consumers of energy and two, that deep energy efficiency comes at a price. The building did not cost extra to build—it was a well-integrated design, built to a typical fixed budget.

On move-in day, when the first wave of 500 occupants entered the RSF, each new resident received a letter from NREL's director, welcoming them to a game-changing facility that would eventually win 40 awards for its architecture, construction, engineering, sustainability, and technology transfer.[23] In 2013, the second phase of the 360,000-square-foot RSF was completed, adding a third wing using the same procurement process, ensuring that the new building would cost less and save more energy than the first phase. After more than 30 years, the majority of NREL staff was finally out of leased office space and into an environment that mirrored its mission.

Perhaps most importantly, the success of the RSF and the buildings that followed had to account for the human factor, monitoring and proactively transforming the usage behaviors of the building's occupants. In essence, a cultural shift was necessary. Shanti Pless joked:

> Buildings would operate perfectly if they didn't have people in them. But the reality is that our buildings are for people. So, on the research side, we spend a lot of time thinking about how people interface with the building, or don't, and the opportunities you can realize in designing that interface well. … What you see in the RSF is the result of multiple years of research on how to best design these systems to enable occupants to do good. And if they forget to turn things off, as we all do, the building is smart enough to make up for that![24]

In the RSF, no lights come on automatically. There are light switches and thermostats everywhere for occupants to use, but daylight and operable windows make overhead lighting and automated HVAC rare necessities (each desk includes a low-wattage task light and a USB-powered fan). Coining the term "occupant engaged," Torcellini and his team developed a philosophy based on a more manual approach to turning things on, with the building maintaining automatic sensors used to efficiently turn things off, if the occupants forget to turn things off. The report concluded that "energy savings from these simpler controls are greater than fully automatic controls."25 The Building Agent desktop app also gave users greater agency over their comfort at work and unleashed the creativity of the contractors in meeting very high energy efficiency and other performance goals for the building.

All these approaches, technologies, and behavioral shifts combined, such that in 2015, six years after it opened, the RSF could still claim the distinction of being the world's largest zero-energy building.

While the building itself has many innovative features, the RSF's sustainable approach extended to the exterior courtyard and landscaping as well. Gabion walls use the site's excavated rocks, held together in recycled steel cages, to form short retaining walls around campus, rather than shipping these materials off-site. Native, arid-climate plants and innovative irrigation and drainage systems minimize the amount of additional water needed for campus landscaping. The system of pipes, swales, and ponds used to carry stormwater offers the pleasant side effect of engendering natural ecosystems for plants and animals, further beautifying the campus.[20]

With a successful template now in hand, the 2012 opening of the 27,000-square-foot Integrated Biorefinery Research Facility incorporated many of the same sustainability principles as the RSF and achieved LEED Gold certification.[26] Associate Laboratory Director Barb Goodman's collaboration with auto manufacturers was made concrete through the opening of the Vehicle Testing and Integration Facility the same year. The campus was growing, and in the right way.

But there was still much work to be done. Without an on-campus parking garage, employees were asked to park in the Colorado Mills Shopping Center—1.5 miles away on the south side of Interstate 70—and be bused to campus.[20] The lack of an on-site food service facility meant that many NREL employees were busing back to their cars midday and driving to find food before repeating the same process to return to campus. For an energy-conscious culture, this was simply unacceptable. As the Grand Buildout continued, mobility and community became central issues.

NREL's on-site cafeteria and parking garage, both completed in 2012, provided two new opportunities for buildings researchers like Pless to "demonstrate best-in-class energy efficiency in another type of facility that we didn't have on campus, which helps us create resources, strategies, and best practices."[24]

Like the RSF, the 12,140-square-foot NREL Café incorporated daylighting, occupant-engaged controls, and waste- and water-minimizing controls, as well as numerous EnergyStar appliances. The practices and technologies used in the LEED Platinum-rated facility are now models for cafeterias at countless corporate campuses, hospitals, and restaurants nationwide. On-site dining also eliminated the need for NREL staff to leave campus so often—cutting down on transportation-related energy use—and provided a cultural opportunity for what many companies value as "creative collisions," the informal and unexpected interactions that occur between often siloed and solitary employees.

Similarly, the parking garage was a highly innovative approach to another ubiquitous commercial structure. Providing 1,800 parking spaces over more than 578,000 square feet on five levels, the NREL garage uses natural ventilation, daylighting, and occupancy sensors to create a facility that's 90% more efficient than similar structures merely built to code. Notably, a 1.153-MW solar photovoltaic array on the garage's roof provides energy for employees to charge electric vehicles at work—another potential game-changer. "Having the option to drive an electric car to work and 100% power it off the sun is a huge technology transition," Pless said. "Our buildings are providing the infrastructure. We're providing the electricity, integrating charging stations into our buildings to be able to offer that to our employees at work. That's pretty powerful."[24]

With these basic campus and employee needs finally solved and evolving, the focus of NREL's Grand Buildout turned back to the laboratories. Next, the state-of-the-art, 182,500-square-foot Energy Systems Integration Facility (ESIF) opened in December 2012, allowing for megawatt-scale testing and modeling of highly complex systems and technologies. The ESIF featured a high-performance supercomputing facility—one of the fastest in the world—and, true to form, NREL aimed to make it one of the world's most efficient as well.

Engineers partnered with Hewlett-Packard to develop a leading-edge liquid-cooled computing platform for its 1-petaflop processor, using warm-water circulation and heat exchangers to cool down the computer processors while using the computer's same waste heat to warm the ESIF's laboratory and office spaces. R&D Magazine named the ESIF the 2014 Laboratory of the Year, and it was the first facility to conduct "integrated research and development of the nation's electrical distribution grid at the 1-MW level."[20]

Whether a high-performance computing center or parking garage or cafeteria or office building, "each of these buildings is a prototype," Carlisle said. As of 2015, NREL's two campuses, South Table Mountain and the National Wind Technology Center, encompass 60 buildings spread over 600 acres. The construction rush of the past two decades has coincided with an executive order by President Barack Obama—first issued in 2009 and made more stringent in 2015—calling for an extraordinary mandate for more federal buildings to conform to net-zero energy building standards by 2020. NREL has long led the charge, and the research gathered over the past few decades will be in increasingly higher demand.

Builders both large and small, catering to individuals as well as major corporations, have become ever more attuned to the importance of designing the whole building with sustainability principles in mind, minimizing the use of energy overall, and maximizing the use of renewable energy rather than conventional electricity or natural gas. Luckily, the technology has reached a point where building with these principles in mind only entails a nominal premium and, many times, can save capital expenses more than a traditional building approach—and the cost curves are all going in the right direction.

> “[What] strikes me about looking at NREL's campus is the history of how we think about what we do. . . and that it is directly reflected in our building designs over the last 40 years. You can literally see the progression knowledge in our 40-year quest to reduce the impact of the built environment.”
>
> – **Paul Torcellini**, Commercial Buildings Research Group Manager

Concurrent with that, came the development of OpenStudio, a software platform that assists architects and engineers in evaluating building energy efficiency measures throughout the design process.[27] NREL's strides in incorporating modeling and computing into the maintenance and operation of buildings is now a standard part of building science curricula in doctoral programs across the country. Many startups are focused on creating operating systems that help builders and occupants better understand and navigate the relationship between building usage and energy performance. LEED certification has become a goal for countless mainstream builders.

While single net-zero energy buildings are now a cost-effective reality, the next frontier is applying net-zero principles to community-wide projects. Economies of scale are a major factor in renewable energy sources as well as integrated systems. Towns like Greensburg, Kansas, which was devastated by a tornado and decided to rebuild 100% renewable—are great examples of what's possible with broad buy-in and commitment. And NREL's two campuses remain proving grounds for this scalability and systems integration.

"We use our own projects as research opportunities," Pless said. "We document what's new or unique about it. How to do it, how to replicate it, for others to learn how to do it. That's how we justify getting involved in this 'Campus of the Future' stuff. It's fine for us to do it, but our goal is to get everyone to do it."[24]

Torcellini put it this way: "[What] strikes me about looking at NREL's campus is the history of how we think about what we do … and that it is directly reflected in our building designs over the last 40 years. You can literally see the progression knowledge in our 40-year quest to reduce the impact of the built environment. We have had the same theme for the entire time and, while the words have changed, the focus has not changed—somewhat amazing!"[16]

Indeed, NREL's campus is an epicenter of net-zero principles and its buildings are living laboratories—proof of the aesthetic, economic, and sustainable viability of our renewable, decarbonized energy future.

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"The Future Looks Bright"
Robert McCall

Chapter 6

Our Culture and People

Introduction—United by a Shared Purpose

Well before he had racked up more than 30 patents and two prestigious R&D 100 Awards, Edwin Tracy was a young researcher at RCA Laboratories in Princeton, New Jersey. Tracy's former Materials Division director at RCA, Paul Rappaport, had recently left to become the first lab director of a place in Colorado called the Solar Energy Research Institute (SERI). In 1979, Rappaport "came back to RCA to give a colloquium about his new digs." In addition to being excited about the scientific opportunities at SERI, Tracy remembers that Rappaport "threw the best freakin' holiday parties. … He set the tone." Tracy applied to SERI and got the gig.

Both Tracy and Rappaport knew how important an organization's mission could be—especially something as essential as renewable energy—but they also understood the importance of having fun. That said, the mission of SERI was clear for Tracy from the beginning: "Everyone coming in during that time felt the same: We're going to try and save the world." He followed Rappaport to Colorado and never looked back.[1]

When Bob Noun first visited SERI in Golden in early 1979, he felt as if it had been tailor-made for him. The young attorney had worked on Capitol Hill crafting foundational renewable energy legislation in the mid-1970s. Not wanting to succumb to "Potomac Fever," he and his family moved to Colorado to start anew.

At SERI, he realized he could continue to pursue renewable energy without all the politics. That next phase of his career would last more than 30 years. And while he would later concede that he had been a bit naïve about dodging politics, he wouldn't have exchanged the chance to join SERI for anything.

"The early days of the lab were, for me personally, the most exciting in my professional career," Noun said. "You couldn't wait to get to work there in the morning. Just because of the brilliant people, young people that had been brought in to do the science and develop the technology that we're seeing today in its third or fourth generation."[2]

Today, new NREL employees feel the same passion. One researcher was so excited to be hired in early 2015 that he arrived in Golden without a change of underwear![3] Fortunately, the Colorado Mills Shopping Center is only a 5-minute drive from the NREL campus.

A community born during the global energy crisis that took place 40 years ago has found renewed urgency in today's uncertain energy landscape, where debates around climate change and global energy sources have the power to divide and unite, to start wars or provide hope for the next generation. Today, NREL and its people are more vital to the fate of the planet than ever. The challenges that the NREL community weathered along the way only strengthen the sense of community among its famously independent-minded employees and position NREL for even more seminal contributions in the decades ahead.

Act I—Pioneering Research, Visionary Leadership

As the first director of SERI in 1977, Paul Rappaport set the standard not only for great parties but also for best-in-class renewable energy research and development (R&D). For more than two decades at the RCA Laboratories, he had been advancing photovoltaic (PV) solar cell science and was a tireless advocate of utilizing solar energy on a commercial scale. "He was a person with a strong technical background who had a knack for translating technical musings into the language of managers of private industry and government agencies," said longtime RCA collaborator Joseph Loferski. "He became the leading ambassador to the photovoltaic community and, ultimately, of the solar energy community to the outside world."[4]

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>
> **– Bob Noun**

While at RCA, Rappaport and Loferski greatly advanced the efficiency of silicon solar cells used to power satellites. They also published the first paper describing a gallium arsenide PV cell. Their pioneering work in using cadmium telluride and cadmium sulfide for solar cells accelerated the adoption of these PV materials in commercial markets.[4]

As distinguished a scientist as he was, Rappaport also had a keen feel for the marketplace and systems-based solutions. "It doesn't make sense to just do blue-sky research," he said in an April 1978 interview with Science News. "To cope with energy, in general, and solar energy, in particular, you have to look at the total system. It is not sufficient to deal with technology only."[5] These prophetic words prefigured NREL's focus on energy systems integration decades later.

In the late 1970s, with support from the Carter administration, Rappaport used the skills he built at RCA to assemble the SERI staff. "The confidence he inspired in people made it possible for SERI to attract an outstanding staff in a very short period of time," Loferski said.4 This staff was described by Science News as "an interdisciplinary team in solar energy the likes of which has never existed before."[5] The team included an all-star group of PV researchers as well as the essential administrators and communicators that could get a young lab off the ground.

One of the outstanding scientists recruited by Rappaport was Lawrence "Kaz" Kazmerski, who conducted groundbreaking research in thin-film photovoltaics at the University of Maine. Among his most noteworthy early achievements was the production of the first copper indium selenide solar cell. Kazmerski would become world-renowned for his thin-film PV work, serving as cofounder and editor of the journal *Solar Cells* beginning in 1979 and, in 1981, receiving the Peter Mark Memorial Award, which is awarded annually to a scientist under age 35 for outstanding research.[6]

That same year, two additional Rappaport recruits would be the first to win a patent for work conducted at SERI. Gene Blakeslee, who had worked for the IBM Research Center, and Kim Mitchell, from Sandia National Laboratories (Sandia), patented a concept for using a multijunction cascade cell to achieve PV conversion efficiencies substantially higher than the average at the time—potentially as much as 40% higher.

Meanwhile, early information technology specialists like Henrietta "Henri" Hubenka had less of a foundation in renewable energy, but quickly found a sense of mission upon arrival at SERI, in large part because of the welcoming culture. "You walked into this office that was free flowing, with people smiling, and you got this sense of warmth and comfort … the feeling of 'Oh my god, this could be a place to really make a huge difference,'" she recalled. "You just wanted to say, 'I don't even care if I get a paycheck, just sign me up.'"[7]

Unfortunately, Hubenka's enthusiasm wasn't met with the same kinds of technology she was used to in other roles. "It was very, very basic. You had typewriters. A small telcom system with an operator," she said. "It was really ground-level compared to other environments."

Despite underwhelming resources, within two years Rappaport built SERI from its original staff of between 30 and 40 to more than 600, with an operating budget of $90 million. Under Rappaport, Science News noted, SERI's solar power brief encompassed "materials, photovoltaics, solar heating and cooling, solar-thermal power generation, agricultural and industrial process heat, wind power, ocean-thermal conversion, and biomass conversion."[5]

Tragically, Rappaport's career was cut short by cancer, and he was forced to step aside in 1979. But he had set a tone for the Institute that would serve SERI and its people well through good times and bad: It's all about the people. In farewell comments to SERI staff, Rappaport said, "My management philosophy has always been that you can do anything if you bring the right people aboard." He passed away in 1980.

But the spirit established by Rappaport lived on, and the parties continued. Moreover, that spirit started having a tangible influence in the lab. "You see someone at a toga party, and you bring that family atmosphere into work with you," Tracy said. "It speeds up the work level quite a bit, not to mention the creativity."

Denis Hayes was selected in 1979 as the second director of SERI. The founder of Earth Day in 1970, and Sun Day in 1978, was a controversial choice, given his lack of scientific training. Some SERI researchers grumbled when Hayes became director without having his predecessor's scientific credentials.[8] However, Hayes clearly saw his role as one devoted to maintaining the excellence of the SERI staff. "I was not hired as a scientist," Hayes said at his initial meeting with SERI staff in 1979. "My job at SERI, as I see it, is to tend the forest by making sure that the best people possible are tending to each of the individual trees. The scientific research program at SERI seems to me to currently be the greatest strength that the Institute has."

> "Kazmerski would become world-renowned for his thin-film PV work, serving as cofounder and editor of the journal *Solar Cells* beginning in 1979 and, in receiving the Peter Mark Memorial Award."

It was a heady few years. SERI's annual budget jumped from $90 million to $130 million—a fund estimated to be more than all other nations together were spending on renewable research at the time. In inflation-adjusted dollars, that budget's high-water mark would not be surpassed for a generation.[9] The staff swelled to nearly a thousand. Renewable energy had arrived.

Among the influx of new employees was Stan Bull, who joined in February 1980. The 39-year-old University of Missouri professor, who had a background in nuclear engineering and radiation physics, was looking for a new challenge.

Bull was leery of SERI's cramped, makeshift labs created out of empty office space, but he was impressed with the caliber of talent. Among the notable researchers he recalls passing in the halls of the Denver West research buildings was physicist Arthur Nozik, who joined NREL in 1978 and specialized in photoelectrochemistry. By the early 1980s, Nozik would have his name on five patents after a decade in the field, and he was just getting started. Another leading scientist was biologist Mike Siebert, who was studying the use of solar energy to split water molecules.[10] Siebert joined in 1977 and helped define the goals of SERI's fuels and chemicals division.[11]

SERI staffers continued to work hard and play hard. A noontime coed softball league was a popular recreational option. Hubenka and researcher Carl Bingham organized group trips—rafting, skiing, and camping—to foster a good work-life balance. And after hours, many SERI staffers grabbed a Coors at one of the nearby bars, not far from the original Coors brewery. The next morning, they came back to their labs to make the world a better place.

Their dream careers were abruptly altered by the reality of budget cuts imposed by the Reagan administration in 1981. Hayes initially hoped that he would pilot SERI through what no doubt would be turbulent times. But he conceded that he probably sealed his own fate by refusing to kill a Carter-era report on what it would take for the United States to get 20% of its energy needs from renewables by the year 2000.[9] For renewable energy researchers, that goal would remain a dream deferred. And then he was, perhaps, a bit too honest.

Hayes was asked to resign but, upon his departure, he lashed out at what he saw as legions of bureaucrats in Washington blocking the adoption of solar energy. Hayes, who would return to his alma mater, Stanford University, to attend law school, delivered a famous parting shot at the U.S. Department of Energy (DOE), describing it as a "dull, gray building filled with dull, gray men, wearing dull, gray suits roaming dull, gray hallways thinking dull, gray thoughts."[9]

Under the new administration, SERI's budget was slashed from $130 million to less than $30 million. Staff cuts were equally brutal. "We went from 1,000 people to 450 almost instantaneously," said Bull, who was working under Acting Director Dan Feucht when Feucht had no choice but to make the cuts.[10]

Those who remained at SERI after the cutbacks were in shock. Many of the makeshift labs were eerily silent and empty by the fall of 1981. The blow to renewable science at SERI would be felt for years. Most of those who left never returned. And several who weren't cut in the initial layoffs were compelled to reconsider their options, which led many to join other academic or research organizations. Two distinguished scientists who had received funding from SERI during its early years—Ahmed Zewail and Alan Heeger—were awarded Nobel prizes in 1999 and 2000 for their groundbreaking work in PV-related research at the University of California, Santa Barbara. But because the cutbacks severed ties between SERI and the researchers, the lab did not share in the Nobel triumph.

Information surfaced over time that SERI might have been killed outright by the Reagan administration if not for the intervention by some surprise supporters. The Coors and Stevenson families were wealthy, conservative Reagan supporters. They were the leaders of a Colorado "kitchen cabinet" of advisers to the president, along with Charles Price, an MRI[1] board member and former U.S. ambassador to the United Kingdom. They realized the value that SERI and its staff were bringing to Golden and the surrounding area and insisted that the president not kill the fledgling lab.[8]

Despite the administration's best efforts to kill SERI, many at the lab refused to be discouraged. Hubenka remembered that during these lean times, there was still a lot of information being disseminated by SERI and, in the era before websites or email, a ton of letters and packages were arriving from interested people.

"I remember at one point we counted 32 gray bins of mail sitting in one office," she said. "People wanted to know about solar, and they wanted to know about what SERI was. At that time, I said, 'These people are going to get answered and we're going to keep the mission moving forward.'"

So Hubenka and another colleague spent a year and a half answering all the letters. "That was the aha! moment," she said. "The feeling of, 'Nothing's going to get us down. I'm not going to say no to these people, and I'm not going to throw this all in the trashcan. We're going to answer every piece of mail!'" In the face of consistent challenges, this impressive sense of commitment—to the growing audience of external supporters as well as the lab's internal morale—would define SERI's culture for decades to come.

Act II—Turning the Corner

Bent, but not broken, MRI brought in Harold "Hub" Hubbard as the new lab director, who positioned himself as the anti-Hayes. "We're going to produce a yeasty research and development environment here," he told the *Associated Press* in September 1981. "One that won't be confused with an advocacy group or a special interest group."[12]

The approach was an astute reading of the Washington zeitgeist. As Bull said, "We just emphasized that foundational research is what we want to focus on. That is what we believed to be more acceptable to the Reagan administration at that time, and that if we just tend to our business, publish, and build a reputation so that we're recognized as sound scientifically by our peers, then we have a case for surviving. It worked."[10] Indeed, the shift in focus was an early indication of the political dance the lab would do for decades.

Throughout the 1980s, SERI juggled staff and management responsibilities to keep the research flowing as smoothly as possible. Employees formed the Staff Council to bring rank-and-file issues to the attention of management. By the fall of 1982, staff and branch chiefs leading different divisions were responding to concerns by focusing on ways to improve the quality and productivity of research as well as management effectiveness.[13]

The Institute's job, and that of its staffers, wasn't made any easier by the fact that the Reagan administration routinely "zeroed out" alternative energy spending from its annual budgets in the early 1980s. SERI had to rely on spending "earmarks" from congressional supporters to fund its work.[14] The following year it was the same story.

Budget cuts kept managers scrambling. Government funding for wind research at SERI and Sandia combined was slashed 90%, from roughly $50 million to $5 million, during the early 1980s.[14] Noun had been doing legal research associated with wind research and had demonstrated "some organizational ability," he said. Hubbard put Noun in charge of the second-largest technical program at SERI on an interim basis until they had the budget to bring in someone with the requisite technical skills.[2]

"The handful of engineers that was working in that program at that time never fully embraced that, but they treated me well," Noun said. "We found an equilibrium where I was able to go out and advocate for the investment in their research and they were able to do the quality science and technology innovation that justified that investment, and it was a happy marriage for 8 years."[2]

By 1984, SERI had the funds to recruit Robert Thresher, one of the top wind researchers in the country, to run the technical side of the program, including the Rocky Flats wind research site about 20 miles away. Tight budgets created opportunities for staffers and managers with good people skills and the ability to bridge disciplines within the Institute.

Barbara Goodman, a single mother who worked her way through the nearby Colorado School of Mines, joined SERI full-time in October 1984 in the bioenergy area. One early assignment was to review an ethanol program and fly to Washington to defend it in front of DOE officials who were threatening to pull the plug. Goodman not only kept the program alive, she secured an increase in funding to $4.5 million.[15] Such success in the face of adversity created career opportunities for Goodman and others during the latter 1980s, despite the fact that SERI's annual funding had flatlined. But a new era was dawning.

Senior chemist John Webb had been with SERI since 1978, scrounging obsolete equipment to fashion solar collectors in the early years and later bouncing from one relatively small project to another. Finally, following the election of George H. W. Bush in 1988, things started to change.

Funding picked up and, at long last, the Solar Energy Research Facility (SERF) was constructed on the South Table Mountain site in 1992. "The opening of SERF is when I could identify that we had finally arrived," Webb said. "When we got SERF, I thought, 'My God, we're going to have a home.'"[16]

By the early 1990s, the Institute had apparently turned a corner. Budgets had slowly been increasing since 1989. Renewables were back on the nation's radar after Saddam Hussein's invasion of Kuwait, and the first Gulf War reversed the late-1980s slump in global oil prices. In fact, SERI had a valued supporter in J. Michael Davis, the president's assistant secretary for energy efficiency and renewable energy, who had previously worked at the lab.

After 15 years, the lab had clearly entered a new era. But the next 15 years wouldn't be as smooth sailing as the early 1990s might have suggested. The researchers and staffers would continue to face funding and organizational challenges even as the campus grew in size and scope. Management and organizational changes aimed at reaping efficiencies seemed at times to be more of a shuffling of bureaucratic chairs. Largely because of these obstacles, the lab would see its scientific status challenged.

> "By 1984, SERI had the funds to recruit Robert Thresher, one of the top wind researchers in the country, to run the technical side of the [wind] program, including the Rocky Flats wind research site about 20 miles away."

Hubbard retired as director of SERI in 1989. Gene Mannella, the former director of Washington operations for the Electric Power Research Institute, succeeded him, but his tenure was short-lived. In less than a year, MRI replaced him with Duane Sunderman, who had served as head of MRI's Kansas City operations for 6 years. Sunderman had previously spent 28 years in various management positions with the Battelle Memorial Institute.[17]

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[1] MRIGlobal is an independent, not-for-profit, contract research organization that operates research facilities for DOE, including SERI (now NREL).

Compared to Hubbard, "Duane was much quieter and maybe a little bit less interactive with the staff, but also a very kind man," Goodman said. "They both had come from MRI and had a lot of the MRI culture and protocols and way of doing business."[15]

A key milestone was reached in 1991 when SERI was elevated to the level of a national laboratory and renamed the National Renewable Energy Laboratory (NREL). The new name more accurately reflected the range of work underway, and the national status gave NREL researchers and staff the sense that their work was now being viewed, in Washington and among their peers, as on a par with that of the other national labs, many of which had been in existence for decades.

Bigger budgets enabled growth in staffing and research projects through mid-decade. And a rush of new construction on the South Table Mountain campus during the first half of the 1990s for solar and biofuels research, as well as the new Visitors Center, provided added momentum, as did the creation of the National Wind Technology Center in 1994 at the Rocky Flats site.

Following Sunderman's retirement, Charlie Gay was named director in late 1994. MRI recruited him in response to a national study that concluded the national labs should be run in a more business-minded way. As the former president of ARCO Solar, a solar PV company, Gay brought an experienced eye for business and controlling costs to the lab. In many ways, his arrival could not have been better timed.

In November 1994, Republicans took control of Congress for the first time since 1954. House Speaker Newt Gingrich's *Contract with America* was focused on slashing the federal deficit, and the NREL operating budget was among the first federal programs to feel the knife. The NREL budget for fiscal year 1996 was cut by 30%, and more than 225 positions were eliminated. Several programs were abandoned or sharply curtailed.

Gay did his best to cut overhead costs, not research activity. "When I got here, it was almost 8 months and well over 130 steps to award a contract, and by the time we had restructured our overhead activities, we had gotten the contract time down to about 28 days and the number of steps necessary to be about a dozen for awarding a contract," he said.[18]

In 1996, Gay returned to the private sector, just as Republicans lost their congressional majority. Gay's successor, Richard Truly, was also focused on operating efficiencies, but as a former vice admiral in the U.S. Navy, he took his inspiration from the military. Truly was frustrated that NREL had engaged in an expensive, consultant-driven reorganization that he couldn't make sense of. He would bring more traditional focus to the organization over the next several months.

> "Truly's efforts to maintain flat spending in the face of constant pressure to cut federal budgets was an accomplishment that many staffers probably didn't fully appreciate at the time."

At the same time, Truly didn't pretend to know more than the front-line researchers did about the R&D being conducted at NREL. And he had nothing but praise for the caliber of researcher and staff alike. "I remember saying to the staff that I was unencumbered with any experience or knowledge of the energy business, and you would have to teach me," Truly said.[19]

Truly's efforts to maintain flat spending in the face of constant pressure to cut federal budgets was an accomplishment that many staffers probably didn't fully appreciate at the time. Yet the constrained spending was clearly taking its toll. NREL was experiencing a brain drain in certain fields as researchers left for better-funded posts in academia or the private sector. And America's lead position in renewable energy research was eroding. As Truly told the members of the Press Club in July 1999:

> Eight European countries now have higher percentage contributions from non-hydro renewables than the U.S.; whereas, in 1990, only one country did. Not that many years ago, the U.S. was ahead in nearly all renewable energy technologies in terms of total domestic capacity installed, market share, and number of companies involved. We are quickly falling behind in each of these measures and losing the leadership role in moving the world to a sustainable energy future.[20]

During the second Bush presidency, war spending, tax cuts, and criticism of the science of climate change dampened spirits for many NREL researchers and staffers. NREL's budget rose modestly in the first few years of the 21st century to peak at $230 million in 2003, though it was still well shy of 1995 spending levels. Cuts would follow in each of the following three years.

Act III—Taking it to the Next Level

Dan Arvizu, who succeeded Truly upon his retirement in 1995, addressed a sea of nearly 900 NREL researchers and staff as he stood in the Denver West Marriott ballroom late that year. A veteran renewable energy scientist and entrepreneur, Arvizu had been recruited by MRI to follow Truly and take NREL to the next level:

> I made the comment toward the end. I said, 'You know, I see the day when all of us are on our own campus all together.' I got some very enthusiastic applause. Then I said, 'and the day when we have our own cafeteria and we could all eat together,' and everybody stood up and clapped. It got a standing ovation. I'll never forget it. It was fabulous. . . . Then I thought to myself: Boy, how are we going to do that? I have no idea how that's going to happen.[21]

Arvizu had clearly tapped an unmet appetite for a greater sense of community among NREL staff and within the NREL campus. He understood that such *esprit de corps* required physical as well as operational improvements. NREL was chronically lacking in infrastructure that reflected its role in U.S. renewable energy research. The building spree of more than a decade earlier had not been continued in any meaningful or strategic way. More than anything, from the standpoint of the campus buildings and behaviors, NREL was not practicing what it preached.

"The lab lacked confidence," Arvizu said. "The lab did not have the kind of we-can-do-it attitude. And what I saw was researchers, very talented people, who were more worried about next month's budget and how they were going to get paid than looking long term at what we can contribute for the long haul."[21]

Arvizu's plan faced some immediate and serious hurdles. Energy Secretary Samuel Bodman visited NREL a short time later. His underwhelming comment—"I really don't have a vision for this place"—left many researchers depressed. Then the lab was confronted with a budget shortfall of $28 million and was forced to reduce its staff by 32 positions. For many remaining staff, it looked as if the lab's fortunes were going from bad to worse, despite the new director's enthusiasm.

Bodman told Arvizu privately to give him the best program ideas he had, and he would promote them to President Bush. NREL teams pulled together quick summaries of leading efforts in solar and biofuels and sent them to the secretary. As it turned out, President Bush was searching for a new theme to highlight in his January 2006 State of the Union address. Biofuels carried the day, and the president delivered what would become known as his "addicted to oil" speech promoting alternative fuels.

Bush planned a visit to NREL the following month to highlight the biofuel efforts. Arvizu received a call from a White House staffer. Did he think he could hire back those people he had just let go? His team reversed the layoffs—rehiring a group soon known as the "laid backs"—in time for the presidential visit, though not before the press got hold of the story. To his credit, Bush did not duck the issue. "I recognize that there has been some interesting, let me say, mixed signals, when it comes to funding," he told NREL employees.[22]

> "That first crowd of people that came into SERI really believed that they could do great things for the world and for the planet. I believe that we've gone a long toward that. We've got a long way yet to go. We're not there. We haven't gotten to our ultimate goal but we're well down the road to making an impact."
>
> – **Stan Bull**, Associate Lab Director for Science and Technology

The renewed focus on renewable energy provided a base on which NREL could build. With Republicans joining Democrats in support of the lab and many of its programs, funding increased. Extensive planning around NREL's "Campus of the Future" provided a concrete foundation for the American Recovery and Reinvestment Act's increased funding for renewables. NREL was perfectly positioned to make use of this influx of capital, and the campus quickly and massively evolved, a period known as the Grand Buildout.

Under Arvizu's leadership, which continued into the Obama administration, NREL researchers also redoubled efforts to work with the renewable energy industry to promote technical innovations and get them to market as quickly as possible. Above all, the mission of NREL remained unchanged—as did the passion of its employees.

"The national laboratory system was born out of creating the atomic bomb. In other words: killing people," Tracy said. "Meanwhile, we're here to save the planet. We have a noble mission. That fosters that type of camaraderie, friendship, and family. That's what makes NREL unique from the whole damn laboratory system."

And despite changing leadership, NREL has been well served by its directors. "I do believe that each and every director was exactly what we needed at the time," Goodman said. "They each brought something that was fundamental to what we needed to take us in evolution to the next era of this laboratory, and I think that's been very important for our success and for our advancement as a national laboratory."[15]

Where does that leave our people? NREL's staff has nearly doubled since those staffers were rehired in 2006. A new generation, much less burdened by funding challenges, is pouring into renewable energy research. It's as if the 1970s are back, at least in terms of the change-the-world spirit these millennials bring to NREL. Research is increasingly focused on tying renewables into the world's energy grids. But Tracy, among others, wants to make sure that the mission remains consistent, and the same fire in the belly that existed in the 1970s is stoked for decades to come.

"The character of the laboratory has changed with this new generation," Tracy said. "So, I'm going to challenge them: They've got a historical esprit de corps that has to be kept up, and I hope they're up to the challenge of doing so."

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NREL Directors — 1977-2016

The first director of the Solar Energy Research Institute (SERI) was **Paul Rappaport**, a physicist by training and a prominent photovoltaics researcher, known by some as the "father of modern solar cell technology." Midwest Research Institute (MRI) recruited Rappaport away from his post at the Princeton-based RCA Laboratories, selecting him for his "proven ability as a research administrator" combined with his "notable technical achievements in the field of solar energy." In his 1977 resignation from the RCA position to take up the mantle at SERI, Rappaport wrote that "there is no way I could turn down this opportunity to lead the solar energy effort for the nation and to be Mr. Carter's principal solar energy advocate." Rappaport was responsible for many of SERI's crucial early hires, including the top positions in five operating divisions as well as numerous researchers who were drawn to SERI largely because of Rappaport's sterling reputation—not to mention his famous Christmas parties. The inaugural SERI directorship was a position he held until he could no longer work. Rappaport died on April 21, 1980, at the age of 58.

After Rappaport came the irascible **Denis Hayes.** An activist first and foremost, Hayes received his undergraduate degree at Stanford and worked with Senator Gaylord Nelson to launch the first Earth Day in 1970. While at Stanford, Hayes had been part of an activist group that had led to the banning of classified research being undertaken at Stanford—a populist, realistic, and grounded approach that would continue to inform his work at SERI. "I was an unusually good crossover," Hayes said, citing his academic history and his time in Washington supporting the development of grassroots policy. At SERI, Hayes was a departure from Rappaport's scientific pedigree. According to Bob Noun, Hayes "had a vision of a renewable energy future and the research and policy initiatives needed to fulfill it."

The biggest influence Hayes wielded was also what led to his departure—a swift move to get copies of a long-brewing report in the hands of peer reviewers and policy influencers before President Ronald Reagan had a chance to entirely slash the Department of Energy. It was a brave and bold move, and one that led to his being not-so-gently encouraged to resign. But his impact on the lab and the broader field of renewable energy would be felt for decades to come.

After Hayes came **Harold "Hub" Hubbard**, known for his interpersonal skills and willingness to jump into anything and everything. Hubbard had been working as a senior vice president of operations for MRI and was ready to shepherd SERI through the trying Reagan years, undaunted by the president's attempts to shut down the Department of Energy. "SERI can continue to function without a DOE," said Hubbard in an interview for Seriatim in 1981. Much of Hubbard's job was reassuring SERI's staff that they would continue to survive regardless of the Reagan administration's lack of interest in supporting renewable energy, and he did so with a blend of enthusiasm and keen strategic ability, navigating some challenging political waters.

Duane Sunderman was director from 1990 to 1994, during what was sometimes referred to as the lab's "renaissance period." Sunderman cultivated President George H. W. Bush's support, which led to SERI being elevated to national laboratory status. The fourth laboratory director was also largely responsible for getting NREL's hybrid electric vehicle program off the ground. Sunderman's steady, quiet brand of leadership was essential during this transformative period.

Charles Gay arrived at NREL in 1994. His corporate background in solar thermal power plant development at ARCO—a company that collaborated with SERI in the 1970s—and later work with Siemens helped him keep the lab afloat during another period of massive budget cuts. "I had been in industry my whole career," Gay said, an experience which led to a comfort with streamlining and cost-cutting that, even if it didn't endear him to the administrators he had to cut, let NREL find its legs.

In 1997, **Richard Truly** became director. A military man who had come up through NASA and flew the Enterprise into space (cracking to a Boeing executive that while he'd flown on a Boeing seven times, he'd never flown in one), Truly brought military precision to the way NREL was run. He spent the first few months reorganizing the lab. Dan Arvizu, Truly's successor, later explained that Truly "wanted to get a seat at the table" for NREL in the realm of politics. Truly also believed that NREL needed to shift its focus from what he termed the "religion" of renewable energy (i.e., "we should do this because it's the morally right thing to do") into a more market-driven focus ("we should figure out a way to make renewable energy cheaper and more efficient than nonrenewable energy as a way of improving people's ability to do what they need to do"). Truly was vital to NREL's shift into applied engineering and commercial deployment.

Dan Arvizu took over the directorship of NREL after Truly retired in 2004. Arvizu had served as an executive in both government and private industry, working at Sandia National Laboratories and, most recently, as chief technology officer of CH2M Hill companies. He came to an NREL that was reinventing itself. From Arvizu's standpoint, energy systems integration was the next big thing and his role was to fully usher NREL into the 21st century where the widespread adoption of renewable energy technology depended on the seamless interplay of increasingly complex, hybrid systems. Blending research experience with keen political sensitivities, Arvizu rejuvenated the workforce and was able to speak as easily to lab scientists as he did to policymakers and the private sector. NREL's Energy Systems Integration Facility (ESIF), opened in 2014, is one of his hallmarks—the built version of his top-down, ultra-integrated approach to science, policy, experimentation, and communication.

With Arvizu announcing his retirement in March 2015, the directorship transitioned to **Martin Keller**, most recently the associate laboratory director for energy and environmental sciences at Oak Ridge National Laboratory. Keller faced a host of challenges and opportunities during the next era of NREL's evolution but, as former Laboratory Associate Director Barbara Goodman said, "I do believe that each and every director was exactly what we needed at the time. They each brought something that was fundamental to what we needed to take us in evolution to the next era of this laboratory, and I think that's been very important for our success and for our advancement as a national laboratory."

Afterword

This body of work is intended to document a specific time period, 1977 to 2016. Much has happened at NREL from 2016 to present day (2022) and the editor acknowledges that the time gap from project completion to publication is significant.

Throughout our 45 years of programmatic advancement, it's true that budget frequently dictates the pace of work. This project is no different. The time and resources of many went into this body of work and finally pushing it into the world was crucial. Other publications have cited this work and bringing it to completion, through publication, was long overdue.

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National Renewable Energy Laboratory
15013 Denver West Parkway, Golden, CO 80401
303-275-3000 • www.nrel.gov

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