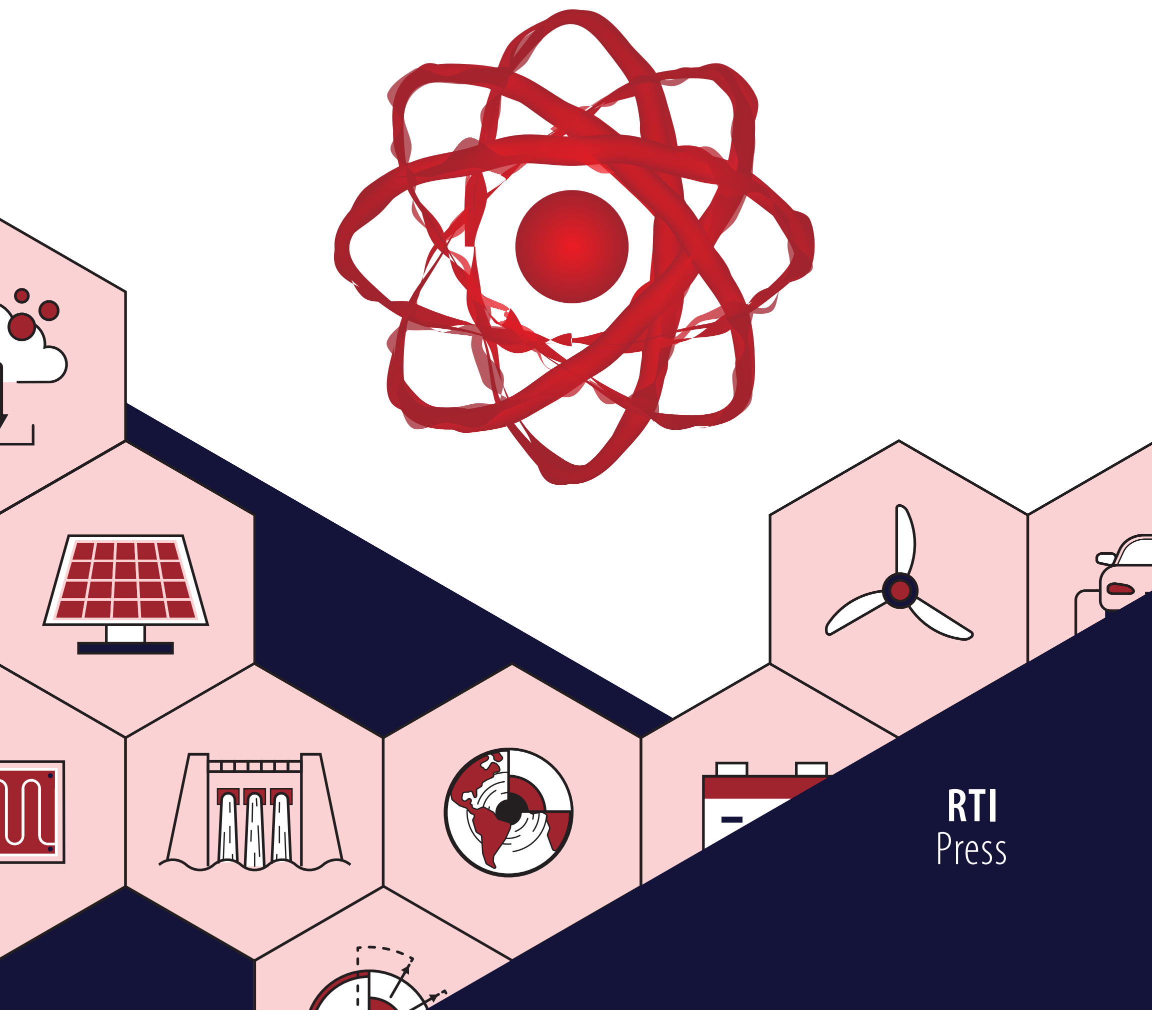
Vikram Rao & Chris Gould

CARBON-FREE POWER

Role of Small Modular (Nuclear) Reactors



RTI Press

Carbon-Free Power

Energy Options in a Carbon-Constrained World

Series Editor

David Dayton

Carbon-Free Power

The Role of Small Modular (Nuclear) Reactors

Vikram Rao and Chris Gould

RTI Press

RTI INTERNATIONAL

Library of Congress Control Number: 2022948166

ISBN 978-1-934831-31-1
(perfect bound paperback)

ISBN 978-1-934831-32-8
(PDF)

ISBN 978-1-934831-33-5
(EPUB)

RTI Press publication No. BK-0027-2301
https://doi.org/10.3768/rtipress.2022.bk.0027.2301
www.rti.org/rtipress

Cover design: Tayo Jaoloso

The RTI Press mission is to disseminate information about RTI research, analytic tools, and technical expertise to a national and international audience. RTI Press publications are peer-reviewed by at least two independent substantive experts and one or more Press editors.

RTI International is an independent, nonprofit research institute dedicated to improving the human condition. We combine scientific rigor and technical expertise in social and laboratory sciences, engineering, and international development to deliver solutions to the critical needs of clients worldwide.

Contents

List of Figures

List of Tables

Preface

There is a new world order in electrical energy production. Solar and wind have established themselves as the low-cost leaders. Even though they can be highly variable over short and long timescales, they are now effectively the *base load* power producers in many jurisdictions.

But electrical power is needed 24/7. Something else must fill the gaps. Other power sources must fit this dynamic. And if the sources are to be carbon free or carbon neutral, and economical, the list of alternatives is short. This book is concerned with one of those alternatives: small modular (nuclear) reactors (SMRs). One of the two other gap fillers, geothermal energy, is described in light detail and is expected to comprise another volume in the series.

Chapter 1 lays out our arguments for considering these relatively new reactors as part of an appropriate energy mix for the future. And for those not especially familiar with the nuclear physics and engineering, Chapter 2 is a short primer on the underlying physics and Chapter 3 provides a summary of the various SMR projects being considered across the globe. Chapter 4 describes how SMRs are different from conventional nuclear plants, especially in the feature of intrinsic safety. This is not a nuclear engineering textbook, and in the heart of the text, Chapters 5–8, we explore how SMRs both fit well with the temporal variability of wind and solar and also open up new industrial opportunities to reduce carbon emissions in more than just the power sector. Chapter 7 details the economics and the expectation that the delivered cost from SMRs will be closer to that of wind and solar than to conventional nuclear.

But public acceptance is a challenge for nuclear of any sort. We do not seek to convince here. Rather, we lay out the facts as we see them, so that readers may make their own judgments on the merits of the arguments for SMRs. Chapter 5 discusses the perception issues, and Chapter 9 summarizes our view of the way forward for energy in an increasingly carbon-constrained world and the role of SMRs in realizing 24/7 carbon-free power.

Glossary

Definitions

Unit acronyms: nano (n) = 10^{-9}, micro (μ) = 10^{-6}, milli (m) = 10^{-3}, kilo (k) = 10^{3}, mega (M) = 10^{6}, giga (G) = 10^{9}, tera (T) = 10^{12}

The **basic unit of energy** is the joule (J). The basic unit of power (energy per unit time) is the watt (W), which is joules per second: 1 W = 1 J/s. The thermal unit is calorie: 1 calorie = 4.2 J and the electric bill familiar to the public, in kilowatt-hours: 1 kWh = 3.6 million J.

The electrical **power capacity** of a plant is given in megawatts and is designated MWe (where the e stands for electrical) to distinguish it from the larger MWt (t for thermal), which is the heat needed to generate the electricity. Typical values for large reactors are 1000 MWe and 3000 MWt.

Capacity factor is the percentage of power capacity delivered. It is the efficiency of utilization of the capacity. Fuel availability often limits capacity factors, most notably in the case of solar power, where monthly median capacity factors can run under 25%.

Energies in nuclear reactions are given in million electron volts (MeV) where 1 eV = 1.6×10^{-19} J. The fission of one U-235 nucleus releases about 200 MeV of heat energy, millions of times more than the few eV of heat released in a typical chemical reaction.

Levelized cost of energy (LCOE) measures the lifetime cost of an energy source, divided by its energy production. Cost comparisons between energy sources are made using this criterion.

Light water is H_2O. Whenever we use the word *water* in the book, we mean light water. In contrast, **heavy water** is D_2O (where D stands for deuterium). For nuclear reactors, the distinction was historically significant because heavy water can sustain a chain reaction with natural uranium, whereas enriched uranium is required with a reactor cooled with light water.

Neutrons involved in a nuclear reaction are characterized either as **thermal** or **fast**. Thermal neutrons are in thermal equilibrium with their environment and have energies of a fraction of an eV, with speeds 2–3 km/s (still quite rapid). Fast neutrons have much higher energies, on the order of an MeV, moving at speeds up to 20,000 km/s.

Radioactivity (nuclear decay) is characterized in **becquerels** (B): 1 B = 1 decay per second. An older term, the **curie** (Ci) is still in common industrial usage: 1 Ci = 3.7×10^{10} B.

Radiation dosage is expressed in **sieverts** (Sv), a unit that measures the health effects of ionizing radiation on humans: 1 Sv = 1 J/kg. The sievert is a very large unit; 5 Sv received all at once over the whole body is considered a lethal dose. An older unit, the **rem**, is still used, especially in industry and the popular press: 1 Sv = 100 rem. Natural background radiation gives everyone an exposure on the order of 2.5 mSv/year or 0.25 rem/year. A chest X-ray exposes the patient to about 0.1 mSv.

Other Acronyms Used in the Text

EIA US Energy Information Administration

HALEU high assay low enrichment uranium: between 5% and 20% U-235

HEU high enrichment uranium: more than 20% U-235

HGTR high-temperature gas-cooled reactor

IAEA International Atomic Energy Agency

IEA International Energy Agency

LEU low enrichment uranium: less than 20% U-235

LMFBR liquid-metal cooled fast-breeder reactor

LWR light water reactor

MSR molten-salt reactor

NNSA National Nuclear Security Administration

NRC US Nuclear Regulatory Commission

PWR pressurized water reactor

SNF spent nuclear fuel

Mind the Gap

Introduction

Some London Underground railway platforms have "Mind the Gap" in large letters on the platform edge. The words are intended to inform passengers of a mismatch between the curving platform and the subway car steps. Today's clean electrical energy sources also have gaps that must be minded. Most obvious are the temporal gaps in the production of electricity from solar and wind. The sun doesn't shine all the time and the wind can vary strongly with the season. For the world to transition to carbon-free or carbon-neutral electrical energy production, these intermittency gaps must be addressed.

Many candidate solutions have been suggested. They include batteries, pumped hydropower, biofuels, geothermal energy, and nuclear power. We will comment briefly on all these options at various points. But because of the unique characteristics and history of nuclear power, we will focus on nuclear, specifically on the role of a class under accelerated development: small modular reactors (SMRs). They offer the promise of being excellent clean energy gap fillers, in part because they are capable of ramping up or down in output to fit any public utilization profile. Importantly, the footprint is small: 100 times smaller than that of a solar installation with the same output, and 1000 times smaller than that of a wind farm. This allows a strategy of mixing and matching with the low-cost leaders, solar and wind.

To proponents, nuclear reactors are an obvious response to the challenge of providing carbon-free electrical power to a growing world. They deliver regardless of whether the sun shines or the wind blows. They have done so for seven decades in US Navy vessels and civilian power reactors. The fuel is readily available. One ton of uranium-235 provides as much energy as 3 million tons of coal (without releasing 6 million tons of CO_2 into the atmosphere) and as much energy as a 10-square-mile solar farm operating for a year.

To opponents, all these advantages may be admitted. But at what financial cost? What about nuclear weapons and nuclear proliferation? How will the waste be disposed of? Above all, what about safety after the events at

Chernobyl and Fukushima? As recently summed up in the *Bulletin of the Atomic Scientists*: "For 70 years, even the most ardent supporters of nuclear energy have readily admitted its four liabilities—cost, safety, waste disposal, and proliferation—without solving them" (Squassoni, 2021).

Our aim in this book is to provide information that enables readers to come to their own conclusions about the merits of a nuclear power solution to the mind-the-gap problem. The issues are not solely technical or economic; they also include perception and societal acceptance. And the issues are not specific to the United States. Countries across the globe are grappling with the challenges of providing resources to people increasingly aware that energy is the key driver in improving living standards. Informed public discourse will be essential for helping societies reach appropriate and equitable energy solutions to the challenges of climate change.

Nuclear Now?

We would not be writing this book if we did not think nuclear energy deserved serious consideration. We discuss the pros and cons in detail in later chapters. But overall, we have three reasons for supporting SMRs as part of a carbon-free energy future:

> **An improvement to the status quo.** The most likely alternative is worse for the planet. And we don't mean solar, wind, and other renewables. We mean doing nothing, continuing on the current path of relying on fossil fuels to deliver the bulk of electrical power. When faced with difficult policy issues, a natural tendency is to defer decisions. Climate change is real, even if the more apocalyptic speculations on the state of the planet 100 years from now are just that, speculations. Undeniable is the premise that we should be reducing greenhouse gas emissions (carbon dioxide, methane) where and when we can. And we can in power generation.
>
> **A complement to solar and wind.** The favored alternative of many, that solar and wind with batteries can do it all, is not supportable in many jurisdictions. As of 2021, they supplied just 13% and 10% of electrical power in the United States and India, respectively. We are aware that the costs of solar, wind, and batteries have dropped dramatically in recent years. But hoping that costs will continue to fall and projecting a 10-fold ability for the United States or India to

scale-up into the future is speculation with little merit, primarily because of the low asset utilization efficiency, even in the best cases. Another hurdle to expansion is the land area required for solar and wind, which is prohibitive. For output equivalent to an SMR facility, solar would require about 100 times the land area and wind about 1000 times. A mix of resources is a prudent way to build into the future, preferably a mix that meshes to optimally serve the dynamics of demand.

A tested technology. Nuclear power has 70 years of global experience—some good, some not so good. For sure, its environmental externalities must be addressed, but they are understood, as in the case of fossil fuels. The same cannot yet be said for the new green technologies with barely a decade of life cycle experience. All technologies come with a cost, and carbon-free energy doesn't automatically guarantee a welcome reception from stakeholders. The lengthy approval process for bringing hydro power from Quebec to New York City is a case in point (see "The Grid Needs Fixing Too" in the box below).

We believe that SMRs can be a significant part of a mix of zero-carbon electrical power resources. Many of the SMR offerings are built upon accumulated experience with conventional nuclear and other industries. One such insight is the key concept of passive safety (see Chapter 3). Another is the vastly improved economics through modular designs (see Chapter 7).

Public perception and societal acceptance will also be key to realizing a carbon-free energy future that includes SMRs (see Chapter 5). The public's concerns with nuclear energy are unique, and often not allayed by messaging that continually emphasizes safety, leading to the obvious conclusion that these must be unsafe if the people in authority keep telling us how safe they are.

The Grid Needs Fixing Too

Clean hydroelectric power from Canada fueling New York City's burgeoning need for energy: Who could object to that? A lot of people, it turns out. From the State of Maine asking why they should cut their trees to provide power line access when they don't get anything from it, to the Environmental Protection Agency with concerns about disturbing PCB deposits on the Hudson River bed, to environmental groups concerned with endangered species and the impact of further dam construction.

The problem of getting power from A to B has been a challenge everywhere for decades, subject to litigation and argument from federal and state oversight groups and concerned citizens. The Canadian project has been on the table for over 17 years. It may finally be close to realization (Dezember, 2022). But that time lag serves to remind that a push to switch to carbon-free renewables consists of more than simply coming up with a location for a solar or wind farm. Delivering the power to where it's needed is just as essential.

The US grid is aging and has had some spectacular meltdowns. How vulnerable is it to cyber attacks or ice storms in Texas? We don't really know. But there is a general principle here: Distributed systems are more capable of responding to problems. Even if supply is interrupted locally, the damage doesn't spread over vast areas, as has happened in Texas and the Midwest. SMRs by their nature are distributed, capable of feeding a local area, adjusting easily as demand increases or populations shift. Nationwide pipeline systems are needed because not every state can produce oil or gas. But every state can produce solar or wind or SMR power. Grid resilience does not mean cutting yourself off from your neighbors. The objective is local or statewide self-sufficiency, not independence.

The Economics of Filling the Temporal Gap

Filling the gaps in solar and wind generation with low- or no-carbon energy has a limited set of options. Today this is accomplished primarily with lithium-ion batteries. They are not inexpensive. If a company like Google wants to claim that its data centers are powered 24/7 100% by carbon-free energy, then just what does having that backup capacity cost them? A July 2021 report from the Rocky Mountain Institute (Dyson et al., 2021) looked at this question and more, by studying US and European grids. They found that it is certainly possible for a corporate entity to be 100% carbon free with solar and wind, but the cost is high because the means of storage is so expensive.

A key takeaway is that filling the gap to achieve anything approximating 24/7 coverage can double or quadruple the cost of generation.

This then is the cost that clean alternatives like SMRs and geothermal need to meet in order to be viable, not the cost of baseline solar and wind. There is the old story of the two men being chased by a bear. One says to the other, "We will never be able to outrun it." The other responds, "Sorry, but I only have to outrun you." And so it goes for SMRs and other aspirants for achieving a 100% carbon-free future.

SMRs have economic advantages over alternative energy investments because they rely on small modular systems, adding units to produce scale. This is counterintuitive because industry has been used to the dogma of the economies of scale. Large plants with high throughput can distribute cost over more production, and the overall cost is lower. But small modular units can compete favorably if the process is designed for a smaller scale, and if economies of mass production can be achieved. While these are early days for SMR deployment, NuScale's design, for example, is projected to deliver electricity at costs well below those of conventional large-scale nuclear power stations. NuScale is the first company to have its SMR design approved by the Nuclear Regulatory Commission and plans commercial deployment in Utah in about 7 years. More details of their approach are in Chapter 3.

We don't exclude other candidates for solar and wind backup. Examples are advanced geothermal systems, innovative storage solutions, methane with carbon capture and storage, and carbon-free hydrogen. SMRs and geothermal systems are projected to deliver at costs under US$70 per MWh. At least two geothermal offerings are likely to reduce the cost to US$40 over time. Early placements of geothermal systems are expected to be in support of data centers, with one already announced as a Google collaboration with the Stanford University spinout Fervo Energy.

Summary

Over the last 5 years or so, a realization has set in that solar and wind are the most cost-effective sources for carbon-free grid systems. But their unavoidable temporal gaps must be filled. In our opinion, these gaps are best filled with some combination of SMRs, geothermal energy, and innovative storage solutions. Only SMR and geothermal are approaching commercial scale.

Of these two, SMR is the more versatile, able to be located almost anywhere, and at varying power levels. The modules are produced in factories and assembled on location. An industry-standard 1-GW assemblage can fit into a 40-acre space. Energy production creates new jobs and brings new industry to locations previously underserved with opportunities. However, societal acceptance of nuclear energy is a hurdle to be addressed.

Until these solutions reach scale in the mid-2030s, natural gas-based generation could be the stopgap, preferably accompanied by carbon capture and storage. Natural gas is a fossil fuel, and a goal of carbon-free electricity is to phase out fossil fuel. But "out with the old and in with the new" is not practical in this case, at least not until gap fillers for solar and wind are at full scale.

In the following chapters we go into detail on the issues touched on here. Consequential decisions will need to be made by local, state, and governmental leaders. All of us need to be informed and to participate in this important debate on what our energy future should be in a carbon-constrained world.

The Future of Fossil Fuel

Coal, oil, and natural gas are fossil fuels relevant to this discussion, in that their phase-out is crucial for achieving climate change mitigation goals. In the next three decades, all three will be in decline, at differing rates. Any such declaration carries the caveat of unusual events that alter the schedule. One such was the Russian invasion of the Ukraine. War is the primary reason for perturbation of secular trends.

Coal has been in decline in the United States for several years, based primarily on the fact that plentiful, lower carbon-intensity natural gas is available at prices competitive with coal-based generation. In addition, most coal has other pollutants, such as NO_x and SO_x emissions, which are difficult to abate. But the United States is unique in its abundance of shale gas. Europe has relied on Russian gas in the main, and the prices are driven by liquefied natural gas (LNG) pricing, which is always at least US$4 per thousand cubic feet over the producer price for natural gas. Tight supplies could drive that higher. But, except for short-term swings, coal will generally be in decline in Europe as well.

India and China are unique in needing to feed fast-growing economies. India is doubling down on solar and wind but is likely to use abundant coal to produce hydrogen as a supplement. This can be done essentially carbon free as technology becomes available for CO_2 sequestration. For India, the driver is a paucity of domestic natural gas. China already produces significant methanol from coal. The same process can be varied to produce hydrogen. Both these countries are likely to keep coal alive longer than high-income countries.

Major oil companies, such as Shell and BP, have already announced the intent to continually reduce oil production. One mechanism has been divestiture, such as Nigerian assets by Shell. This could mean continued production by someone else, with an increase in flaring of associated gas (Tabuchi, 2022). Eventually, though, oil will continue to decline due to demand destruction.

Natural gas will be the longest lived of the trio. An important reason is that until zero-carbon augmentation to solar and wind comes onstream, it is the cleanest cost-effective alternative. As noted in Chapter 6, the long-term alternatives will not hit their stride until the mid-2030s. If combined with carbon capture, tolerance of natural gas could be extended.

In summary, all three fossil fuels will be in continual decline at differing rates regionally. Natural gas could even see a bit of an uptick in the next decade because of an inconvenient truth: New solar and wind capacity results in more natural gas usage, for the long-duration gaps in output. The antidote for that malady would be acceleration of the long-term alternatives, such as SMRs, geothermal, and innovative storage. That's going to need policy changes.

References

Dezember, R (2022) Can Quebec's dams power New York City? Blackstone is betting $4.5 billion on it. *Wall Street Journal*. https://www.wsj.com/articles/can-quebecs-dams-power-new-york-city-blackstone-is-betting-4-5-billion-on-it-11645180226?mod=searchresults_pos2&page=1

Dyson, M., Shah, S., & Teplin, C. (2021). *Clean power by the hour: Assessing the costs and emissions impacts of hourly carbon-free energy procurement strategies*. RMI. https://www.rmi.org/insight/clean-power-by-the-hour

Squassoni, S. (2021). Nuclear energy: A distraction on the road to climate solutions. *Bulletin of the Atomic Scientists*, *77*(6), 290–294. https://doi.org/10.1080/00963402.2021.1990488

Tabuchi, H (2022). Oil giants sell dirty wells to buyers with looser climate goals, study finds. *New York Times*. https://www.nytimes.com/2022/05/10/climate/oilfield-sales-pollution.html?smid=url-share

Nuclear Physics, Nuclear Energy, and Nuclear Weapons

Introduction

To help readers understand how energy is created and harnessed through nuclear technology, and to provide context for our later chapters on small modular reactors (SMRs), we offer here a brief introduction to nuclear reactors, including some of the background nuclear physics. While the material is quite technical, it's not necessary to follow every detail; feel free to skim and come back later as needed.

Units

The basic unit of energy is the Joule (J). In nuclear physics, the more common unit is the electron-volt (eV): 1 eV = 1.6×10^{-19} J. The basic unit of power (energy per unit time) is the Watt (W): 1 W = 1 J/s (s = second). A more familiar energy unit in an electric bill is the kilowatt-hour: 1 kWh = 3.6×10^{6} J. The power generated by a plant is given in megawatts and is designated MWe (e = electrical) to distinguish it from the larger MWt (t = thermal) heat needed to generate the electricity. Typical nuclear power plant values are 1000 MWe and 3000 MWt.

In 2021, utility-scale power plants in the United States had a generating capacity of 1.1 million MW and provided 4.1 trillion kWh of electrical energy: about 60% from fossil fuels, 20% from nuclear reactors, and 20% from renewables (EIA, 2022). Wind and solar produce their 20% share directly. The other 80% share comes from power plants that produce heat energy that is then converted into electrical energy, at about 30% efficiency.

One appeal of nuclear power is clear: 1 ton of uranium-235 will fuel a 1000-MWe plant for a year, whereas 1 ton of coal will fuel a comparable fossil fuel plant for about 10 seconds. The reason? A nuclear reaction can release 10

Table 2.1 Number of power plants in countries with the largest deployment of nuclear power

US	France	China	Russia	Japan	Korea	India	Canada	Ukraine
96	58	48	38	33	24	22	19	15

Source: IAEA (2020).

million times the energy of a chemical reaction. Another appeal is that it can be almost *always on*. US nuclear plants made up only 8% of the 2021 US generating capacity and yet provided 20% of the energy delivered.

As of 2020, 443 nuclear power plants were operational worldwide (Table 2.1). About 70% of these are *pressurized light-water moderated and cooled reactors* (PWRs). Light-water moderated and cooled means that normal water (H_2O) is used both to slow the fission neutrons and to carry off the heat generated by nuclear fission. Pressurized means the reactor is at high pressure to prevent the water from boiling.

PWRs became dominant due to the early decision by Admiral Hyman Rickover to adopt that type for the US nuclear submarine fleet. This chapter focuses on how PWRs work, and particularly on how they are controlled, which is important for understanding what's the same and what's different about SMRs.

Nuclear weapons and nuclear reactors are inextricably linked and have been ever since the first reactor was built by Enrico Fermi in 1942. This linkage endures in the public mind, as we discuss later. For background on the proliferation questions relevant to all nuclear systems, including SMRs, see the brief section on nuclear weapons near the end of this chapter.

A Short Nuclear Physics Primer

Chemical elements are characterized by the number of electrons (Z) surrounding the positively charged nucleus: $Z = 6$ for carbon, 92 for uranium. The nucleus of the atom contains Z protons to bind the electrons, and N neutrons to stabilize the proton core, which would otherwise fly apart. A nuclide is an atom with a definite N and Z. The mass number $A = N + Z$ is used to distinguish isotopes (nuclides having the same Z and different N). For example, C-12 has 6 neutrons, C-13 has 7.

Stabilize is a relative term here because only 288 of the approximately 3000 known nuclides are long-term stable; that is, they live longer than the lifetime of the solar system. Most decay *radioactively* back toward the so-called *valley of stability*.

Radioactive decay is the process of emitting alpha particles (He-4 nuclei) or beta particles (electrons or positrons) along with gamma-rays (high energy photons). Elements that do this are known as radionuclides, characterized by their half-life, defined as the time for half the nuclides to disappear. A feature of this process is that the original emitting atom transforms to a different species. This continues until a stable species is reached. No element heavier than lead ($Z = 92$) is stable. U-235 decays with a half-life of about 700 million years, and U-238 has a longer half-life of about 4.5 billion years. That is why natural uranium today is 99.3% U-238 and only 0.7% U-235 even though they were created in similar amounts billions of years ago in supernova explosions. Radioactive decay is responsible for most of the heat emanating from the center of the earth. This is manifested in phenomena like hot springs and is utilized in the creation of geothermal energy.

As well as radioactive decay, nuclides can undergo nuclear reactions that release huge amounts of energy, 200 MeV in the case of fission. Figure 2.1 shows fission of U-235 by an incoming neutron. More neutrons come out than came in, giving the possibility of a chain reaction if an outgoing neutron can be caused to collide with another U-235 nucleus. It is easy to see how this multiplication leads to massive releases of energy.

Figure 2.1 shows one of many fission paths. Subsequent radioactive decays of barium and krypton, the fission product elements, continue to release energy, contributing to the cumulative fission yield and the afterheat of spent fuels.

Figure 2.1 Example of a fission reaction releasing three fast-moving neutrons and about 200 MeV of energy

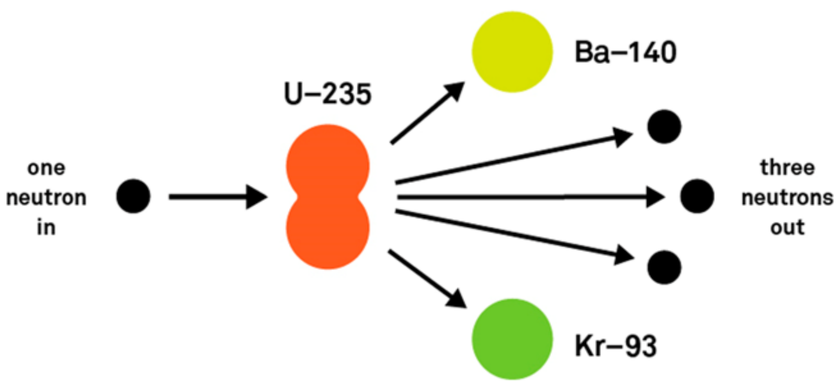
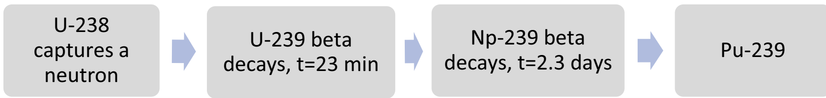


Figure 2.2 Breeding of fissile Pu-239 from stable U-238 by neutron capture followed by two beta decays

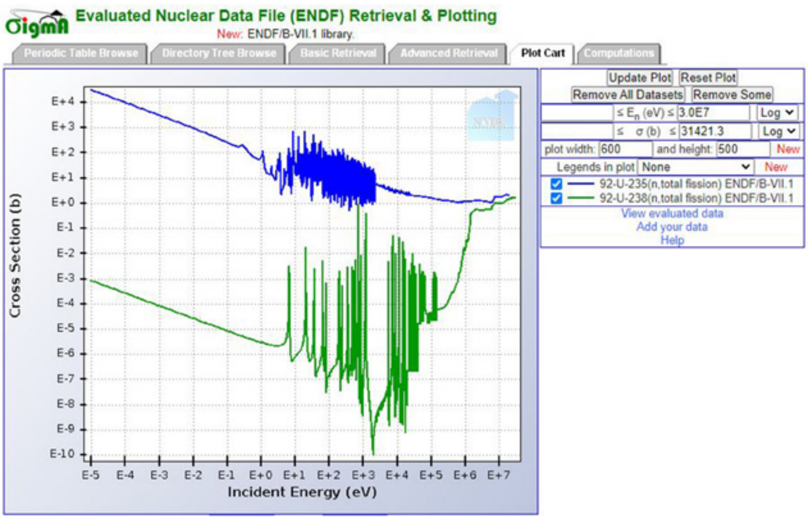


The neutrons in a reactor are characterized as either thermal or fast. Thermal neutrons are in thermal equilibrium with their environment and have energies of a fraction of an electron volt, with speeds 2 to 3 km/s (still quite rapid). Fast neutrons have much higher energies, on the order of a million electron volts, and are moving at speeds up to 20,000 km/s. U-235 fission can be initiated by a thermal neutron, hence U-235 is described as a fissile nucleus. It is the only one found naturally. Three other fissile nuclei are known: U-233 and the plutonium isotopes Pu-239 and Pu-241.

Creating fissile nuclei from stable *fertile* nuclei is called breeding (Figure 2.2). The appeal is simple. Instead of having available for fuel only the 0.7% of uranium that is fissile U-235, the other 99.3% of the element, non-fissile U-238, can now be utilized by converting it to fissile Pu-239. Similarly, abundant Th-232 can be converted to fissile U-233. No pathways exist to breed U-235, though, so once it is used up, it is gone. Thorium-based energy production is important for nations such as India that have vast deposits of thorium but very little uranium. Of course, breeding of Pu-239 for nuclear weapons was the purpose of all the early reactors.

Probabilities for nuclear fission to occur vary widely with the energy of the incoming neutron. The technical term for the probability is the *cross section*. The larger the cross section, the greater the probability. Figure 2.3 shows the huge fission cross section at low energy for U-235 compared to U-238, for which fission probability below a million electron volts or so is negligible. Both curves show resonances (spikes) where the probability jumps up. The resonances in the U-238 cross section are particularly useful. They indicate energies where capture of a neutron is very probable, leading to Pu-239. The spreading-out behavior of the resonances as the uranium fuel temperature goes up (called Doppler broadening) is a valuable feature for controlling an operating nuclear reactor.

Figure 2.3 Fission cross sections for U-235 (upper) compared to U-238 (lower) as functions of neutron energy



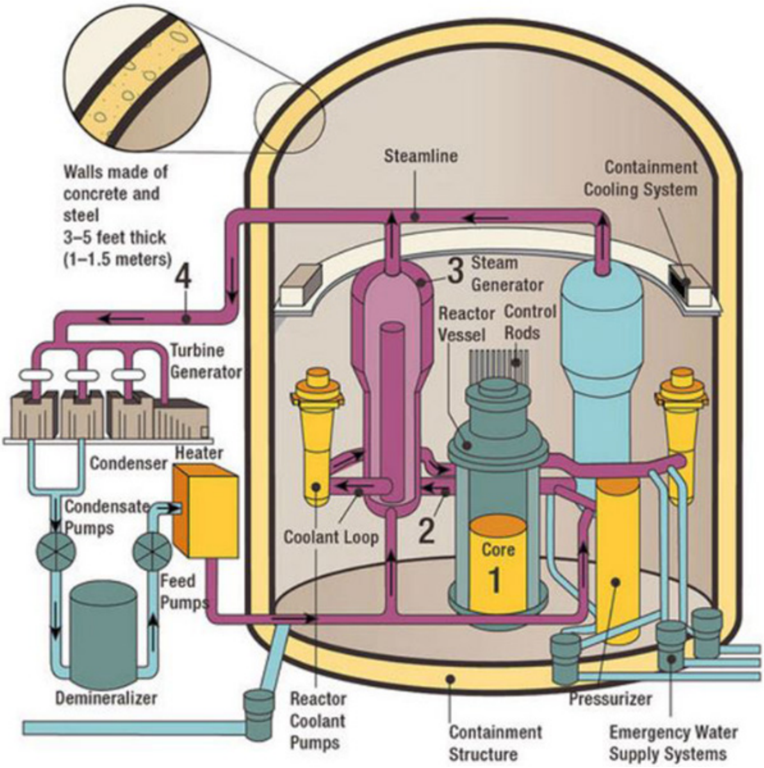
Note: U-235 is readily fissionable down to very low neutron energies. In contrast, U-238 is not fissionable below about 1.5 MeV (part of the reason why you cannot make a bomb with U-238).
Source: National Nuclear Data Center (2011).

Nuclear Reactors

Figure 2.4 shows the layout of a PWR plant. A sense of how large things are is useful. The reactor vessel is typically 12-m high, 5 m in diameter, and made of 30-cm-thick steel. The reactor core sits at the bottom and is a 4-m diameter, 4-m high cylinder of about 200 fuel assemblies, each assembly containing about 200 fuel rods. Each assembly weighs close to a metric ton, most of which is the enriched uranium oxide fuel. It all sits inside a steel and concrete containment structure capable of (in the US) withstanding the impact of a fully loaded jetliner.

In operation, fission of U-235 in (1) the reactor core produces heat, which is carried off by water in (2) a closed coolant loop, called the primary. The water in the primary loop is at about 500°C but does not boil because it is at very high pressure, 150 atmospheres (atm). The water of the primary acts both as a neutron moderator to slow the neutrons down and as a coolant. The primary carries heat to (3) the steam generator where water in a second closed loop, the secondary, is vaporized and transported via (4) a steam line to a turbine. At this point, all heat-to-electricity power plants—coal, oil,

Figure 2.4 Layout of a pressurized water nuclear reactor power plant



Source: NRC (2015).

natural gas—are similar. The steam out of the turbine is cooled in a condenser before returning to the steam generator. Having two separate closed loops is a feature of a PWR; no potentially radioactive primary water reaches the turbine, and fission products remain in the first loop within the containment facility.

A PWR requires slightly enriched uranium for fuel (3% to 5% U-235 instead of the 0.7% of natural uranium). This is due to the relatively high probability that the protons in the water will absorb a neutron as it slows down. (Heavy-water reactors and carbon-moderated reactors can run on natural uranium.) The fuel is in the form of small pellets loaded into a long thin-walled tube—the fuel rod—made of a Zr alloy; zirconium has a low probability for absorbing neutrons. The rod has the important function of retaining all the radioactive fission products, including substantial quantities of gases such as tritium, krypton, and xenon. The rod is filled with helium at high pressure (25 atm) to partially compensate for the pressure (150 atm) of the cooling water flowing outside. The pressure at the end of a fuel cycle will approach 100 atm or more.

The fuel assembly has vacant positions into which control rods and monitoring equipment can be lowered. The control rods contain materials that are highly absorbent for thermal neutrons, removing them from the chain reaction process, hence their name. Boron is particularly suitable, and boric acid is often added to the water coolant. The next section looks at reactor control in more detail.

Reactor Control

A nuclear reactor core cannot explode like a nuclear bomb; the enrichment is far too low and dispersed. Nevertheless, to avoid runaway surges in power levels, which could increase temperatures enough to melt the reactor core, the chain reaction process must be controlled carefully, ideally by mechanisms that do not depend on human intervention. It has been known since the days of Fermi's first reactor that physics principles govern this, and we discuss three of them—delayed neutrons, absorption of neutrons by U-238, and the water moderator—in the context of the multiplication factor, k.

Multiplication Factor

In 1942, Fermi organized a series of lectures for the people working with him on the Chicago reactor. He introduced the definition of the multiplication factor, k, as "the number by which one multiplies the number of neutrons in one generation to find the number of neutrons in the next generation." A sentence in the transcribed notes shows his fondness for the slang he was picking up from his younger colleagues: If $k = 1$, the reaction is self-sustaining, while if $k \gg 1$, "run quick-like behind a big hill many miles away" (Fermi, 1942, p. 216). The related term, *SCRAM*, likely derived from the colloquialism for leaving the premises in a hurry, lives on as the standard word for rapidly shutting down a reactor. In legend, it is printed on a large red button to initiate the shutdown.

From Figure 2.1, one might assume that $k = 3$, but this is not necessarily so. Not all fissions produce three neutrons, and many may escape, or be absorbed by non-fissioning materials. Reactors are designed to operate with k very close to 1.

Delayed Neutrons

The first and most important controlling mechanism relates to delayed neutrons from the fission event itself. Not all neutrons emerge instantaneously. A small fraction, 0.65%, come from the radioactive elements created in the initial fission process. Some are delayed by up to 10 seconds or more. This is much longer than the thermal capture time for prompt neutrons, 0.2 milliseconds. The difference in the timescales has a dramatic impact on how easy it is to control the reactor. The prompt neutrons are captured so rapidly that one can imagine they are all gone by the time the delayed neutrons emerge. By arranging the reactor to be subcritical ($k < 1$) with the prompt neutrons, but supercritical ($k > 1$) only when the delayed neutrons arrive, the timescale for control is now set by the delayed neutrons. The expectation is that the fuel, the moderator, and the control rods have been physically arranged so that k is always very close to unity and controlling mechanisms will adjust k up and down to keep the neutron number steady.

Reactor Control Time

Taking as an example $k = 1.001$ (barely supercritical), and assuming all prompt neutrons captured in 0.2 ms, the neutron number will grow exponentially as $exp(t/\tau)$ with a time constant $\tau = 0.2\ ms\ /\ (k - 1) = 0.2$ s. That's impossibly short. The power will grow by a factor of 150 in 1 second. But now consider the delayed fraction $\beta = 0.65\%$ with the delay time $T = 10s$. We get instead $\tau = \beta T\ /\ (k - 1) = 65\ s$. Neutron growth is slow, and readily amenable to control by automatic adjustments of the control rods and other mechanisms. Reactors are operated in the $(k - 1) < \beta$ regime, where the reactor is critical solely because of the delayed neutrons.

Doppler Broadening

As noted earlier, the spikes in the fission cross section curve for U-238 indicate energies where neutrons are particularly likely to be absorbed. The spikes broaden out (Doppler broadening) as the temperature of the fuel increases, making it more likely that a neutron will be captured on its way to thermalizing. This occurs during the slowing down process. It is a loss process for fission since these neutrons are no longer available to be absorbed by U-235. As the power goes up, the fuel heats up and the number of remaining thermal neutrons goes down. Conversely, as the power goes down, the fuel cools off and the number of thermal neutrons goes up.

Thermal Expansion

The third mechanism has a similar effect to the Doppler broadening. As the power goes up, the cooling water becomes hotter. It expands, becoming less dense. As a result, there are fewer hydrogen atoms to slow the neutrons. More neutrons are now lost to capture by U-238 and other materials.

These two temperature-dependent effects—Doppler broadening and thermal expansion—allow for a measure of responding to energy demand for a powerplant, a desirable feature because electricity produced must be balanced by energy used; there is no storage capability. It works as follows: If demand drops, the amount of steam going to the turbine is reduced. As a result, the temperature of the condensed water downstream of the turbine goes up. This warms the water in the primary loop, which also causes the temperature of the fuel to rise. Both warming effects cause the neutron number to go down, allowing the reactor to be restabilized at a new lower power level. The opposite happens if demand goes up: The fuel and primary water cool off, and the neutron number stabilizes at a new higher power level.

The Reactor Operating Cycle

Startup is a slow and complex process taking many hours (from a warm state) or days (from a cold state). A cold start involves running the pumps to heat up the primary water and pressurize the core. Once the core is warmed, control rods are carefully withdrawn, the reactor becomes critical ($k = 1$) and is slowly brought from zero up to nominal full power. A turbine trip (sudden shutdown) leaves the reactor warm and pressurized so the heating phase isn't required, and the process is faster.

The power of a reactor is proportional to the amount of U-235 in the fuel rods and to the neutron flux (neutron density multiplied by speed). As the U-235 is used up, the power goes down unless the neutron flux is increased. This is accomplished by suppressing the neutron flux at startup with an excess of neutron absorber. The absorber is called a burnable poison. Boron is a common choice, in both the control rods and the cooling water. If the poison and the fuel are used up at the same rate, the flux can remain constant. Overall, poisons take care of long-term neutron flux changes. Control rod adjustments and the two temperature effects handle short-term changes. Boric acid in the cooling water, since it spreads throughout the core, smooths out local flux variations.

Reactor Poisons

A poison in a nuclear reactor is a substance that readily absorbs thermal neutrons. Its presence suppresses the neutron flux required for fission reactions. If there is enough of it, the reactor will shut down. In certain upset conditions, that is the intended function of control rods. Boron was mentioned above as a useful poison that allows control of the power level of a reactor over the life cycle of a fuel assembly.

An unstable isotope of xenon, Xe-135 (half-life 9 hours) is also a poison and can be problematic, since it is produced copiously in fission. In steady state in a reactor, it is burned up (by absorbing a neutron, it is transformed to an isotope with low neutron cross section) at the same rate that it is created. But if the power level drops suddenly, the neutron flux is too low to burn it up and it accumulates as a poison, making the raising of power difficult or impossible until it has decayed away. This was a problem at Chernobyl.

Eventually the percentage of U-235 drops so low that no amount of adjustment can keep the chain reaction going, and the reactor needs to be refueled. During refueling, every 12 to 18 months, about a quarter of the assemblies are replaced by fresh assemblies, and the others are moved around to maintain uniformity of power production. Any one fuel assembly typically spends about 48 months in the reactor. The spent fuel still contains fissile material: about 1% U-235, 1% Pu-239, and other actinide elements. The presence of Pu-239 is noteworthy; it was all produced as the reactor operated and contributed about a third of the total energy release.

Handling and storing the spent fuel assemblies is extremely challenging. Even though the fission process has terminated, the rods are still producing substantial heat due to the various radioactive decay products created. At shutdown, this is about 6.5% of the original thermal power. It drops rapidly but is still about 10 to 15 kWt per assembly after a year; uncooled, that is hot enough to make things glow red (as in an electric range stovetop burner). The assemblies are kept in on-site storage facilities, cooled with water. After 5 years, the activity is low enough that they can be stored in air. Even then they must be heavily shielded. The radiation level at the surface of an assembly can approach 100 Sv/h, enough to deliver a fatal dose within 3 minutes.

As has been noted many times, the key to safe nuclear power is keeping the reactor and the fuel cool—everything else is *easy* by comparison. There have been three notable accidents in the history of the nuclear energy sector: at Three Mile Island in the United States, at Chernobyl in what was then the Soviet Union, and at Fukushima Daiichi in Japan. The last two were the most serious, and the one at Fukushima has cast the longest shadow on the industry. All involved failing to keep reactors or spent fuel assemblies cool. In a later chapter we review these accidents and discuss ideas for passive control of SMRs. In such systems, control against catastrophic runaway is accomplished without human intervention.

Nuclear Weapons

A nuclear explosion requires rapid assembly of a supercritical mass of fissile material. It can only be sustained by fast neutrons, traveling at close to 1% of the speed of light. As we saw earlier, exponential growth (multiplication factor $k > 1$) can occur with thermal neutrons. But to have any significant nuclear yield, about 45 generations are needed (Mark, 1993), and this must occur before the assembly heats up and expands apart, becoming subcritical. Thermal neutrons move too slowly. In appropriate fissile material on the other hand, fast neutrons are reabsorbed to initiate another fission in about 10 nanoseconds. If $k \sim 3$ (no significant neutron losses), a chain reaction can run to completion in less than a microsecond. This is short enough to satisfy the implosion requirements for Pu-239 weapons, and well below the millisecond requirement for a gun assembly, as in the case of the Hiroshima U-235 bomb.

Table 2.2 Critical mass values for three nuclear fuels under two conditions

Fuel/value	Bare (no reflector) (kg)	15-cm Be reflector (kg)
U-235, 19.75%	782.2	143.8
U-235, 93%	53.3	11.7
Pu-239, 93.6%	11.5	3.7

Source: Glaser (2006).

What constitutes a critical mass of fissile material is not a unique number. It depends on the shape of the material, what kind of neutron reflectors surround it, and the density of the material itself. Typically, one thinks of a spherical shape. Reflectors such as beryllium bounce neutrons back into the sphere and create more neutrons by splitting apart under the bombardment of escaping fission neutrons. The density dependence is the key factor, however. Doubling the density means the neutron has to go only half the distance to initiate another fission. The volume is now down by one-eighth, and the critical mass is now one-fourth what it was at normal density. This allows prior assembly (and storage) of a subcritical mass, which only explodes (becomes supercritical) once it is compressed. All implosion weapons are designed with this in mind.

Table 2.2 lists some critical mass values (at normal density). The low values for plutonium stand out. International Atomic Energy Agency (IAEA) designates 8 kg of plutonium as a *significant quantity*. Most nuclear weapons states utilize plutonium.

The primary concern about weapons and nuclear fuels has to do with enrichment of the uranium fuel. PWRs operate with U-235 enrichment of 3% to 5%, much too low to support assembly of a critical mass. But one certainly can imagine higher enrichment—albeit at increased fuel cost—to extend the time between refueling. This is already the case with smaller reactors, especially research and naval reactors, and several SMR designs are proposing higher enrichment fuels. At a certain point, a threshold is crossed where the enrichment level becomes a concern for nuclear weapons proliferation. This level is 20%. Fuel below this is defined as low enrichment uranium (LEU). Fuel above 20% is high enrichment uranium (HEU). The IAEA defines HEU as “direct use nuclear material” and considers anything above 25 kg of HEU “a significant quantity.”

The question of whether a bomb can be made from 20% material has been discussed extensively (Glaser, 2006) for many years. The consensus seems to be that while it is "not impossible," it is so impractical as to be an extremely unlikely path for a group or a country seeking to build a nuclear capability. The issue is evident from Table 2: How could two massive subcritical pieces be brought together in a sufficiently short time to produce a supercritical mass?

Why You Cannot Make a Bomb Out of U-238

Inspection of the right side of Figure 2.3 might lead one to think that highly abundant U-238 could be used to make a bomb. It is, after all, fissionable by fast neutrons. Two things prevent this. First, the fission cross section drops rapidly to zero below about 1.5 MeV (this doesn't happen with U-235 or Pu-239). Second, collisions with U-238 itself almost immediately drop the neutron energies below this threshold. Not even an infinite stack of U-238 metal can explode.

Conclusion

We have summarized here a large amount of material on nuclear physics, nuclear reactors, and nuclear weapons. In several places, we noted the values of physical quantities such as half-lives, delayed neutron fractions, and fission probabilities. If a number of these had been much different, there would be no story about nuclear power and no story about nuclear weapons. If the half-life of U-235 had been half what it is, there would be none left in the world—no weapons. If the fission probabilities were factors of 10 smaller, nuclear weapons would likely be too massive to be practical. If the delayed fraction of neutrons was zero, there would be no way to control a reactor—no nuclear power (at least until nuclear fusion is made to work as an energy source).

Would nuclear power have been developed if not for the push to build nuclear weapons? Probably yes, and possibly with different reactor designs. But even so, much has been learned over the last 60 years. The global challenges today are different. SMRs are an opportunity to revisit nuclear power with fresh eyes and fresh ideas. We review these in the next two chapters.

References

Fermi, E. (1942). *Collected papers* (Vol. 2). University of Chicago Press.

Glaser, A. (2006). On the proliferation potential of uranium fuel for research reactors at various enrichment levels. *Science & Global Security*, *14*(1), 1–24. http://dx.doi.org/10.1080/08929880600620542

International Atomic Energy Agency (IAEA). (2020). *Nuclear power reactors in the world* (Reference Data Series 2). https://www.iaea.org/publications/14756/nuclear-power-reactors-in-the-world

Mark, J. C. (1993). Explosive properties of reactor-grade plutonium. *Science & Global Security*, *4*(1), 111–128. https://doi.org/10.1080/08929889308426394

National Nuclear Data Center. (2011). *Evaluated Nuclear Data File (ENDF) retrieval & plotting*. https://www.nndc.bnl.gov/sigma/

Nuclear Regulatory Commission (NRC). (2015). *Pressurized water reactors*. https://www.nrc.gov/reactors/pwrs.html

US Energy Information Administration (EIA). (2022, January). Table 7.2a. *Monthly Energy Review*. https://www.eia.gov/totalenergy/data/monthly/archive/00352201.pdf

Small Modular Reactors: What They Are, What Makes Them Different

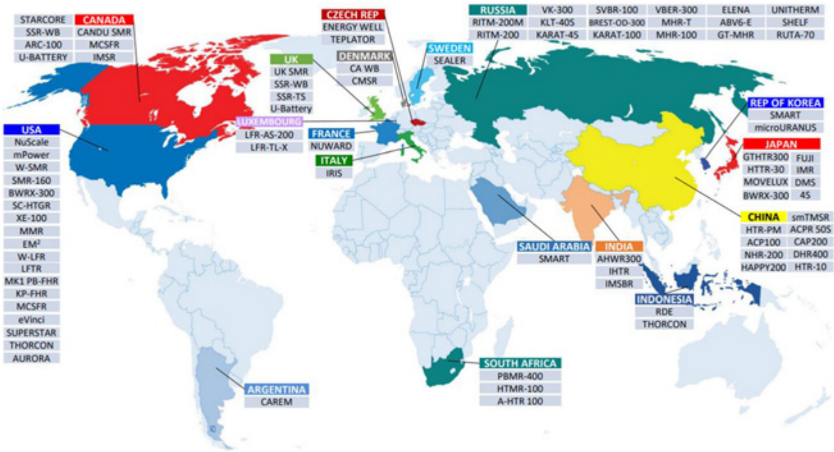
Introduction

Almost every country with experience in nuclear power is exploring the potential of small modular reactors (SMRs), in many cases reviving concepts that were investigated decades ago and then abandoned as pressurized water reactors (PWRs) grew ever larger and, at least at the time, more cost effective. As of 2021, the International Atomic Energy Agency (IAEA) listed more than 70 entries in its inventory of SMRs under development (IAEA, 2021). Figure 3.1 shows the regions and the various companies and governmental agencies participating. The United States is active, but by no means the leader. Nor is any other country. The world is moving ahead on multiple fronts. Systems have already been deployed in China and Russia, and Argentina's *Central Argentina de Elementos Modulares* (CAREM) project is scheduled to go critical in 2023.

While no formal definition exists, SMRs are generally considered to produce less than 300 MWe per reactor, small compared to the typical 1000 MWe for a conventional PWR. *Modular* indicates that SMRs will be produced using modern manufacturing and construction approaches adapted from shipbuilding and aerospace industries. This contrasts with the substantial, bespoke, capital- and time-intensive investments required for conventional reactors. The expectation is that SMRs will have more predictable costs and delivery schedules. They will be designed to be duplicated as additional capacity is needed. As a result, the potential market may be much larger than for current full-size nuclear power plants. Many countries simply do not have the grid capacity to handle a large plant and will be looking for ways to develop mixed-generation grids.

The SMR projects in the IAEA inventory fall into four general categories. Following are their technical names, along with the characteristics that make them attractive beyond just electric power production. Sometimes the words *advanced* or *innovative* are attached to these categories, particularly the last

Figure 3.1 The broad international interest in SMR development



Source: IAEA (2021).

three. But that's a distraction. All the designs have new features even if they build on previously tried concepts. Importantly, they all incorporate lessons learned about safety by the nuclear industry over seven decades.

- Integral PWRs: design building on decades of experience in similar conventional reactors, well suited to achieve fast commercialization
- High-temperature gas-cooled reactors (HTGRs): highest operating temperature of any reactor, opens cogeneration possibilities, such as hydrogen production
- Liquid-metal cooled fast-breeder reactors (LMFBRs): smallest waste stream of any reactor because radioactive wastes are utilized as fuels
- Molten-salt reactors (MSRs): fuel and coolant combined in a liquid, no risk of damage due to fuel assembly overheating, proliferation resistant

The designs built on existing technologies are likely to have an easier path to regulatory approval and commercialization. The non-PWR designs, while having more novel features, cannot be expected to reach commercialization stage as rapidly. They could, however, play important roles because they open new opportunities—decarbonization of industrial processes, hydrogen production, synthetic fuel production, desalination—that have not previously been part of the thinking about nuclear power. In all cases, these SMRs can be expected to substantially augment solar and wind capability.

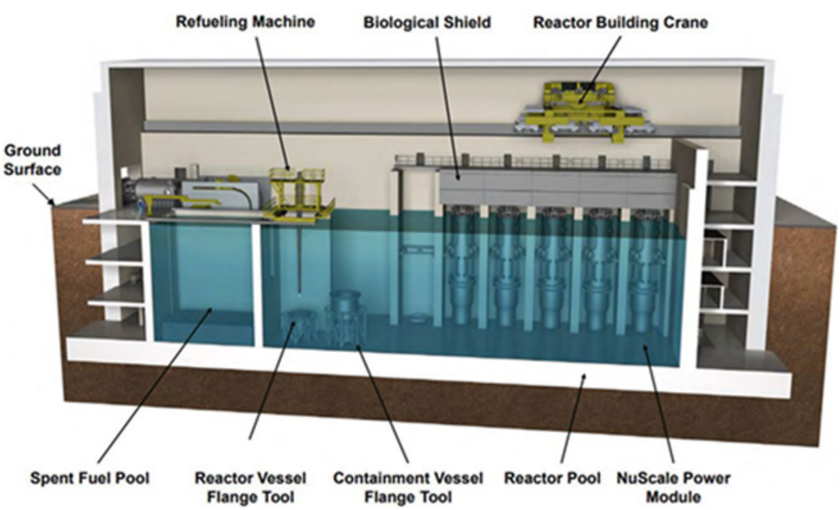
This chapter will take a brief look at some examples of each category, including a fifth category, microreactors, which are of value in specialized applications such as medical isotope production. Chapter 4 will take a deeper dive into safety, proliferation, and waste issues.

Integral Pressurized Water Reactors

These are the most evolutionary of the four designs, and among the most popular options being pursued. The key integration feature is to put as much as possible—reactor core, reactor vessel, steam generators, pressurizers—in a single standardized package. Thermal power is lower, so the large PWR primary circulation pumps mentioned in Chapter 2 are eliminated. Instead, gravity (and the resultant convection) moves the cooling water around. If the reactor shuts down unexpectedly, passive cooling can last many days, even indefinitely: Convection moves the heat, and conduction through the water surrounding the reactor vessel dissipates it to the surroundings. This is an essential intrinsic safety feature, the ability for the reactor to cool down in an upset condition without human intervention.

The proposed power levels vary. Argentina's CAREM project is rated at 30 MWe. In the United States, a NuScale unit (Figure 3.2) will generate about 77

Figure 3.2 NuScale-proposed PWR



Note: An SMR farm would have multiple power modules independently turned on or off as demand or maintenance requires.
Source: NuScale (2012).

MWe. NuScale (https://www.nuscalepower.com/) envisages SMR farms with up to 12 reactors, each unit driving its own turbine. Fuel cycles are comparable to conventional PWRs, about 24 months.

High-Temperature Gas-Cooled Reactors

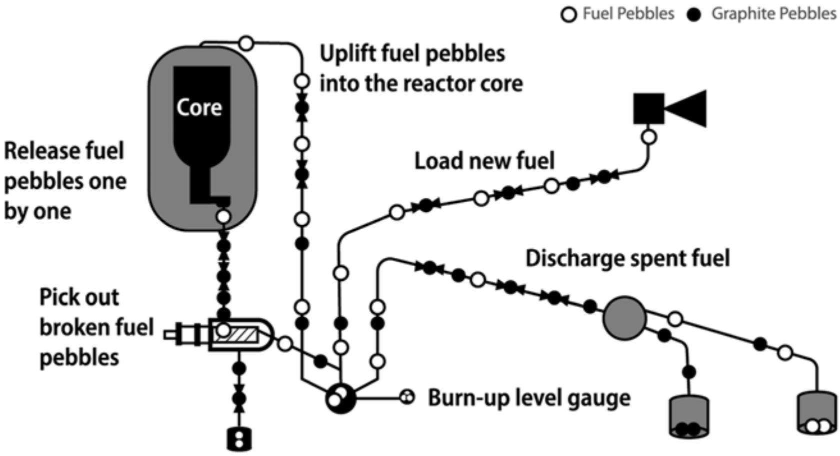
Coolant temperatures in PWRs are limited to 320°C to prevent water-zircalloy chemical reactions that degrade the strength of the fuel cladding. The efficiency of a PWR is accordingly only about 30%. Using helium gas for cooling instead of water allows for much higher temperatures, 800°C or more, at which point the efficiency approaches 50%. The hot gas can drive a turbine, and the residual gas is still hot enough to drive thermochemical decomposition of water into hydrogen and oxygen. High-efficiency, carbon-free hydrogen production, simpler design, and fewer components are appeals of HTGR. An additional feature is that helium is chemically inert and does not absorb neutrons.

Most HTGRs operate with thermal neutrons, using graphite as the moderator. The power per unit volume is low compared to a PWR: 5 MW/m^3 vs 100 MW/m^3. Because of this, the residual heat of the core can easily be dissipated by conduction through the walls. The reactor can be set to shut itself down if the temperature gets too high. Helium flow is not required.

The key to making all this work is a different type of fuel, called TRi-structural ISOtropic (TRISO). TRISO dates to the 1960s and is a mixture of uranium, graphite, and ceramic material in small particles, which are then formed into billiard ball–sized spheres (called pebbles, and the associated reactor is known as a pebble bed reactor). Tested to 1800°C, it is designed to not melt or release fission products (Office of Nuclear Energy, 2019).

China has taken the lead in reviving high temperature reactor (HTR) technology. In late 2021 an industry–Tsinghua University consortium brought online a system, HTR-PM (Figure 3.3), consisting of two pebble modular (PM) reactors, each 250 MWt, together driving a single steam turbine generating 210 MWe. This will be an important test of the long-term capabilities of the technology. If the system operates successfully, ramp-up to a *reactor farm* operation like that of NuScale, with six 250-MWt modular reactors generating a total of 600 MWe, is planned.

Figure 3.3 Fuel handling in China's version of an HTGR



Note: The reactor has hundreds of thousands of the billiard ball fuel spheres. Online refueling involves taking some out every few minutes, checking them for damage, and then recycling them back in or discarding them.
Source: Adapted from Dong (2018).

Liquid-Metal Cooled Fast-Breeder Reactors

Using molten metal to cool a reactor may at first seem strange. But these reactors have a long history and were among the first to be built after WWII. Metals have a very high heat capacity and are therefore effective at transporting heat out of the core. A mercury-cooled plutonium-fueled reactor called Clementine ran at Los Alamos from 1946 to 1952.

Metal-cooled reactors operate at atmospheric pressure, simplifying construction. Sodium and lead–bismuth have been the most extensively studied, in part because they don't readily absorb neutrons. They are not ideal materials, of course. Sodium reacts violently with water. Lead–bismuth attacks metal unless an appropriate oxide layer is maintained. Difficulties on this last point led the Soviet navy to abandon lead–bismuth in its submarine fleet.

The initial civilian drive to construct these reactors was to breed fuel from the otherwise unusable U-238 (see Figure 2.2), thus the term *breeder reactor*. As it became clear that uranium was not in short supply, and enrichment of U-235 was cost effective, interest waned. The interest now lies in the ability to consume the long-lived nuclear waste and the potential for very long fueling cycles, decades or more.

A US experiment in 1984 with the sodium-cooled Experimental Breeder Reactor-II demonstrated its remarkable safety capability. Operators induced a failure scenario by turning off all the pumps and all the power. They then watched as the reactor shut itself down in minutes, relying solely on the convection of the molten metal to cool the transient heat surge. No operator intervention was needed. It ran for about 30 years, producing 62 MWt and 20 MWe. This model is the basis of the Canadian project (ARC-100 from ARC Energy, https://www.arcenergy.co/) to situate a 100-MWe sodium-cooled reactor at an existing nuclear plant at Point Lepreau, New Brunswick. TerraPower (https://www.terrapower.com/) in the United States is also pursuing this technology. Construction of a 345-MWe fast neutron reactor (Natrium project) is slated to commence in 2024 at a retired coal-fired plant in Wyoming.

The Little Reactor That Could, but Eventually Did Not

Two scientists from the Los Alamos National Laboratory came visiting about 2003. One of us (VR) led the ventures investing group for Halliburton, and they were pitching a new concept for an SMR. This thing was going to be the size of a large telephone booth or large ATM kiosk, be emplaced underground, be unmanned, and not need maintenance for 5 years. The output would be 27 MWe and about twice again that thermal. It was liquid-metal cooled. Most important was the safety feature that it was incapable of meltdown. This last intrigued me, and the elegant simplicity bears repetition here.

The fuel for most reactors is enriched uranium (U-238, with between 5% and 20% U-235) in metal or oxide form. In their concept, the fuel would be uranium hydride (UH_3). The hydrogen atoms would act as moderators to slow down the neutrons to allow fission (see Chapter 2). Because they are the same size as neutrons, the energy transfer is excellent. The best analogy is from the game of pool. When the cue ball strikes the eight ball, which has the same mass, the transfer of energy causes the eight ball to move while slowing down or stopping the cue ball.

If the reactor core accidentally overheated to >550°C, the hydride would dissociate and release hydrogen gas. When the population of hydrogen atoms dropped enough, it would be insufficient to moderate many neutrons. This would slow the fission reaction, and the reactor would cool down. In effect, this was an elegant, inherently safe feature because the overheat condition would cause a cool-down with no outside intervention. In conventional reactors, control rods are inserted with elements that have high neutron capture cross sections. This insertion requires motive power, which would be absent if power was lost.

Another elegant feature of the reactor was the handling of the spent fuel. First, refueling was done only every 5 years, and a design target was to extend that to 10 years. Second, the fuel rods would be processed in novel fashion to separate the spent elements. The rods would first be heated to remove the hydrogen. Then they would be inserted in a zone refiner. In principle, this involves creating a very narrow zone of molten metal using a circular heating element, usually an induction coil. This zone is moved very slowly along the length of the rod. The spent fuel elements preferentially partition to the liquid zone (because they have a lower energetic state in the liquid than in the solid they are exiting), leaving essentially pure uranium in the solid behind the zone traverse. The liquid zone continues to be enriched in the spent elements and is pushed to the end of the rod and cropped. The little cropped cylinder can then be appropriately processed to recover fissionable elements or disposed of.

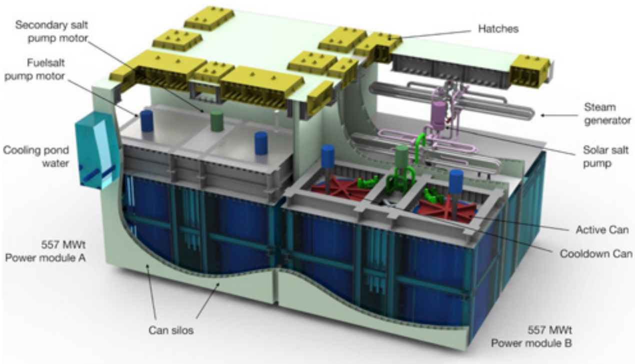
Sadly, this elegant technology never saw the light of day. It was licensed to Hyperion Power Generation. A company announcement in 2009 stated that they abandoned the hydride approach because of perceived delay with certification by the Nuclear Regulatory Commission. They moved to a nitride. Hyperion became Gen4 a few years later. In 2019 Gen4 declared bankruptcy.

The little reactor that could, ultimately could not.

Molten-Salt Reactors

MSRs continue the idea of using a melted solid for a coolant by going one step further and combining the fuel in the molten coolant. This is intriguing because the ever-present concern about fuel overheating is removed; the fuel is already molten. The fuel is usually enriched uranium fluoride. Several designs mix in thorium fluoride to breed U-233.

Figure 3.4 Thorium-powered reactor ThorCon planned for Indonesia



Source: ThorCon (2022).

The United States studied MSRs in the 1960s and gained experience with how they functioned. But compared to liquid metal reactors, the long-term experience with them is much more limited. Nevertheless, projects are pushing ahead, including ThorCon (https://thorconpower.com/) in Indonesia, and the Copenhagen Atomics (https://www.copenhagenatomics.com/) waste burner from Denmark, both thorium fueled.

ThorCon (Figure 3.4) is a thermal design focused on power production and thorium conversion. It is called a fission island and will consist of 250 MWe modules, each containing two sealed Cans. The Can holds the reactor and is the heart of the system. At any one time, one of the pair of Cans is producing power and the other is in cool-down mode. Every 4 years, the Can that has been cooling is replaced with a new one.

The Copenhagen Atomics Waste Burner project, as its name implies, is targeted at burning up the large inventories of spent nuclear fuel while breeding new fuel from thorium. The developers are strong believers in computer control of system protocols to eliminate human errors or the necessity of having humans respond to alarms. For a final system, they envisage a 100-MWt reactor module the size of a 40-foot shipping container, heavy-water moderated, fueled by thorium and the plutonium from spent fuel. At scale, they believe a rate of one module a day construction is possible. Burn and breed projects like this are ambitious but deserve serious consideration as they address head-on the plutonium disposal issue.

Microreactors

By comparison with most SMR concepts, microreactors—some also called nuclear batteries—have very low thermal power, at most 10 to 15 MWt. They use many of the technologies discussed earlier, but in smaller systems that can function with virtually no supervision, or even no on-site operators at all. A fascinating proof-of-principle of the latter is the Oklo natural nuclear reactors phenomenon from earth's early history (Davis et al., 2014).

Oklo Natural Nuclear Reactors

Oklo, in Gabon, was the site of uranium mines supplying France's nuclear programs. In the 1970s, samples of the uranium ore were found to be depleted below the expected 0.7% of U-235. There were also anomalous amounts of isotopes of samarium and neodymium, consistent with production by fission reactions. Subsequent detailed studies suggested that naturally occurring reactors of thermal power on the order of 50 kW had operated there 2 billion years ago when the enrichment of U-235 on the planet was about 4%. The reactors operated for tens of thousands of years, turning on and off on something like a self-regulating 30-minute cycle: water flows in, the reactor starts up, the water boils away, and the reactor shuts down.

Prokaryotic bacteria should get credit for these reactors, for oxygenating the Earth's atmosphere over the prior billion years. Stable uranium oxides are insoluble. But given enough extra oxygen, soluble oxides can be formed, which can then dissolve into lakes and streams. As the bacteria decayed, the oxides were reduced back to insoluble forms. The oxides precipitated out to form layers that could be made critical under the right conditions of enrichment and water moderation. The co-evolution of the geosphere and the biosphere has a long and fascinating history.

Recalling that the US Navy's nuclear program was the forerunner of the PWR industry of today, we mention one microreactor project, Project Pele (US DoD, 2022), that perhaps will play a similar role in revitalizing the US nuclear industry. The US Department of Defense (DoD) electrical energy requirements are substantial, about 30 billion kWh a year (that's 1% of the total US needs). The DoD is particularly interested in microreactors for remote power capability and is funding construction of a prototype HTGR at the Idaho National Laboratory. Two US manufacturers, BWXT Advanced Technologies and X-energy, have designs that meet the DoD criteria: fully transportable, 1 to 5 MWe, and a minimum of 3 years full power operation. The reactor will have similarities to the gas-cooled reactor from China described earlier, using TRISO fuel and able to operate at high temperatures.

Another target application for nuclear batteries is the manufacture of radionuclides for medical imaging. One such isotope, molybdenum-99, is produced copiously in fission, with a half-life of 66 hours. It is the source of technetium-99m (see the following box), a 6-hour half-life isotope used daily in 40,000 to 50,000 procedures in the United States. For many years, the supply chain involved small reactors using high-enrichment fuel supplied by the United States. Concerns about having highly enriched uranium widely circulating, and a pending shutdown of an important Canadian source, prompted initiatives to either move away from reactor production completely or find a cost-effective way to produce it in low-enrichment fueled reactors (Ruth, 2020). Of course, 90% highly enriched uranium fuel will produce 20 times more Mo-99 than 4.5% low enriched, and right away that presents a cost challenge. The short half-lives also imply a continuous production stream: irradiate for 6 days, cool for a day, extract in a co-located processing facility, repeat. Several companies are exploring reactor and nonreactor options, some funded in part by the US National Nuclear Security Administration, charged by Congress in 2012 with finding a non-highly enriched uranium solution to the potential shortfall. In principle, one could conceive of dedicated SMRs for the Mo-99 production, sited close to where it is needed because of the short half-life.

Radioisotopes for Imaging

The most common radioisotope for imaging is technetium-99m (Tc-99m). Its utility lies in the fact that it decays to Tc-99, emitting 140 keV photons, which is an ideal energy level for detection with conventional gamma ray cameras. The images are used for various diagnostic procedures. In most instances, the Tc is injected into the patient and tracked.

Tc-99m is a radioactive decay product of molybdenum 99 (Mo-99). Mo-99 is a product of U-235 fission and is separated from the other fission products as a solution. This solution is adsorbed onto alumina, which is placed in a cylinder. The cylinders are enclosed in shielded containers and shipped to imaging centers and hospitals.

The Mo-99 is continuously decaying to Tc-99m in the *technetium generator*. The generator is flushed periodically with saline solution, which takes out the Tc-99m, leaving behind the Mo-99 to continue to generate. Since the Tc-99m has a half-life of only 6 hours, this is done essentially on demand. The Mo-99, with a half-life of 66 hours, will typically last a week in each generator. (Source: Ruth 2020)

References

Davis, E. D., Gould, C. R., & Sharapov, E. I. (2014). Oklo reactors and implications for nuclear science. *International Journal of Modern Physics E*, *23*(4), 1430007. https://doi.org/10.1142/S0218301314300070

Dong, Y. (2018). *Design, safety features and progress of HTR-PM*. https://www.gen-4.org/gif/upload/docs/application/pdf/2018-02/gif_webinar_htr-pm_dong_201801v2_final.pdf

International Atomic Energy Agency (IAEA). (2021). *Technology roadmap for small modular reactor deployment* (IAEA Nuclear Energy Series NR-T-1.18). https://www.iaea.org/publications/14861/technology-roadmap-for-small-modular-reactor-deployment

NuScale. (2012). *Slide 9: Reactor building houses NuScale Power Modules™, spent fuel pool, and reactor pool*. https://www.osti.gov/servlets/purl/1840518

Office of Nuclear Energy. (2019). *TRISO particles: The most robust nuclear fuel on Earth*. https://www.energy.gov/ne/articles/triso-particles-most-robust-nuclear-fuel-earth

Ruth, T. J. (2020). The shortage of technetium-99m and possible solutions. *Annual Review of Nuclear and Particle Science*, *70*(1), 77–94. https://doi.org/10.1146/annurev-nucl-032020-021829

ThorCon. (2022). *Design*. https://thorconpower.com/design/

US Department of Defense (DoD). (2022). *DoD to build Project Pele mobile microreactor and perform demonstration at Idaho National Laboratory*. https://www.defense.gov/News/Releases/Release/Article/2998460/dod-to-build-project-pele-mobile-microreactor-and-perform-demonstration-at-idah/

Small Modular Reactors: Safety, Proliferation, and Waste Disposal

Introduction

This chapter is about how small modular reactors (SMRs) stack up regarding safety, the risk of proliferation, and the handling of nuclear waste compared to traditional large-scale reactors. Although SMRs and traditional reactors share fundamental principles, design and scale differences result in some important distinctions for these three major concerns. To preview our conclusions, SMRs have substantial safety advantages and potentially lower proliferation risk. However, concerns about waste have not been resolved. For readers interested in details beyond those discussed in this chapter, the Union of Concerned Scientists issued an important 2021 report on the pros and cons of SMRs, focusing on these three concerns and specifically on the newer, more innovative proposals without the track record of light-water reactor technology (Lyman, 2021).

Who's in Charge?

Before delving into differences between SMRs and traditional reactors, it is important to understand who regulates safety, proliferation, and waste disposal. This is particularly pertinent for plutonium—we mentioned earlier how little of this element you need to make a nuclear weapon—and also for tritium, a component for boosting the yield of a nuclear weapon.

The Need for Plutonium and Tritium

The United States is no longer operating reactors to produce weapons-grade plutonium. It has more than enough in storage. It has even declared 60 tons surplus, awaiting disposition. Tritium (hydrogen-3) is another matter. Its 12.3-year half-life means it must be replaced in warheads on a regular schedule. Lacking a currently operating reactor, the agency with responsibility, the National Nuclear Security Administration (NNSA), uses the nominally civilian Watts Bar power reactor of the Tennessee Valley Authority (TVA) to produce tritium. That is not difficult, as neutrons readily break up Li-6 into tritium and an alpha particle. TVA is a quasi-governmental agency. The blurring of lines between the Nuclear Regulatory Commission (NRC), TVA, and NNSA is a continuing challenge for policy makers and regulators.

The legal authority for civilian uses of nuclear power in the United States is the NRC, created as an independent agency by Congress in 1974. Anyone wanting to build or operate a nuclear reactor needs NRC approval. Other countries have agencies with similar mandates. The following is from the NRC website:

> The NRC regulates commercial nuclear power plants and other uses of nuclear materials, such as in nuclear medicine, through licensing, inspection and enforcement of its requirements.

The International Atomic Energy Agency (IAEA) is the closest equivalent to a global NRC. Signatories to the 1968 Treaty on the Non-Proliferation of Nuclear Weapons agree to allow IAEA inspectors to monitor their reactor operations to ensure proper accounting of fissionable materials. The only exceptions to this inspection regime are France, China, Russia, the United States, and the UK, countries that exploded a nuclear weapon prior to January 1, 1967. The Treaty has 191 signatories and is one of the more widely accepted arms control agreements.

The Comprehensive Test Ban Treaty, dating to 1996, went further in seeking to ban nuclear explosions completely. To be formally ratified, more nuclear power states need to sign on. Though not formally in force, the treaty effectively brought atmospheric testing to an end.

SMRs will be regulated by the NRC in the United States. One may expect the IAEA to play a similar role globally, at least for the nonnuclear-weapon states. The legal landscape, though, is potentially quite complicated. A reactor built in one country may now be transported to another country to operate. Whose responsibility is it to deal with safety, proliferation concerns, and waste disposal? Cross-border issues may be much more in play with SMRs than with conventional reactors because SMR components, relying on economies of mass production, could well be sourced from several countries. The parallel for this holds in solar panels, most of which are manufactured in China today. Correspondingly, countries with faster processes for approving and operating SMRs may have an advantage in bringing them to the global marketplace.

Detailed examples of SMRs were discussed in Chapter 3. Here generic features as they relate to safety, proliferation, and waste disposal will be discussed. The first order of business is to review the notable accidents that are on everyone's mind when they think about nuclear power.

The Notable Nuclear Reactor Accidents

Catastrophic accidents that destroyed power reactors have occurred at Three Mile Island in the United States, at Chernobyl in Ukraine in the former Soviet Union, and at Fukushima Daiichi in Japan. In all three cases, failure to maintain cooling of the reactor core was the cause, and in the first two cases human error was a significant contributing factor.

Three Mile Island, 1979

Unit 2 was a 1000-MWe pressurized water reactor (PWR). The accident began when the main feedwater pump (secondary loop; see Figure 2.4) malfunctioned, causing (by design) the generator to trip and the reactor to shut itself down. So far so good, except that backup feedwater failed to kick in because a valve had been left closed by mistake. The pressure in the reactor vessel rose, and (again by design) a relief valve opened to vent the steam. It was contained and that was OK. But the valve stuck open, and the operators now misread the status of the reactor itself. They shut off the main cooling pumps and an emergency core cooling system, thinking the core was filling with water when in fact it was now partly uncovered. The core did not melt but was severely damaged.

The accident was a combination of design failure (insufficient information of the reactor status), equipment failure (sticking valve), and operator error (valve closed that should have been open, incorrectly turning off cooling systems).

PWRs underwent considerable upgrading and review after this incident. There has been no accident with a PWR in the 40 years since. Nevertheless, the accident did happen, and mistakes by human operators cannot be discounted.

Chernobyl, 1986

Arguably a more willful human failure, a graphite-moderated, water-cooled 3200-MWt reactor was deliberately put into an unsafe situation as part of a test to confirm that emergency core cooling could be maintained while the main generator spun down. The test presumed the power level would be reduced to 700 MWt, but instead it ended up at 30 MWt. This is a level at which xenon poisons are not burned up (see Chapter 2 box, "Reactor Poisons"), and quickly raising power back up is almost impossible unless all the control rods are withdrawn. This is a prescription for disaster in a graphite-moderated reactor: A local hot spot can turn into a steam void, at which point the power can rise exponentially. By some estimates, it reached a 100 times its design level in just a few seconds. The reactor was blown apart. The graphite caught fire, spreading radioactive debris across many countries. It's unclear whether a containment vessel, standard in PWRs but not present in this design, could have contained the explosion.

The exact sequence of events continues to be debated (World Nuclear Association, 2022), but all agree that there were two explosions, a few seconds apart, the second bigger than the first. The design of the reactor included a 2000–metric ton cover with multiple access holes for online refueling. Each hole was sealed off by a 350-kg cap. The standard explanation was that the first explosion was due to steam lifting off the cover, exposing the core and triggering a second hydrogen explosion. Recently, a Swedish group (De Geer et al., 2018)—from the reactor facility that first alerted the world to what had happened in Ukraine—put forth an alternate explanation: The first explosion was a runaway reaction in individual still-intact fuel channels, blowing off the caps and sending jets of radioactive material through the roof into the sky. The second explosion followed as the steam lifted off the lid and exposed the full core to air.

Chernobyl was by far the most serious nuclear reactor accident in history. While operational failures triggered it, the main takeaways are that the design was inherently unsafe, and nuclear accidents can have global consequences. For example, the German prohibition of nuclear power was caused by the Fukushima Daiichi accident. We have criticized the operators at Chernobyl, but we would be remiss in not noting heroic service by them and others after the explosions; 28 died from radiation sickness in the following months.

Fukushima Daiichi, 2011

This accident was initiated by an earthquake that caused a tsunami that inundated the reactor site about 50 minutes later.

The Fukushima Daiichi power complex consisted of six boiling water reactors producing a total power of 4700 MWe. At the time of the earthquake, Units 1 to 3 were operating, and Units 4 to 6 were shut down. The earthquake triggered an automatic shutdown of the operating reactors. Off-site power was also lost, in part due to a mismatched socket on a backup line. At this point, the situation was still recoverable. But the tsunami arrived, destroying the emergency diesel generators, inexplicably located below ground level, and much else, creating a total station blackout for Units 1 to 4. The operators had no mechanism for cooling the afterheat. Over the course of the next few days, the cores became uncovered, resulting in major damage. Recovery involved pumping in large amounts of seawater, which became radioactive and presented a subsequent disposal problem.

The complex is fully shut down. There are no plans to restart or rebuild any of the reactors.

While the initiating events cannot be attributed to human error, the Japanese Fukushima Nuclear Accident Independent Investigation Commission that investigated the event was far less charitable, bluntly labeling it "a manmade disaster." Quoting from the Chairman's opening comments

> THE EARTHQUAKE AND TSUNAMI of March 11, 2011 were natural disasters of a magnitude that shocked the entire world. Although triggered by these cataclysmic events, the subsequent accident at the Fukushima Daiichi Nuclear Power Plant cannot be regarded as a natural disaster. It was a profoundly manmade disaster—that could and should have been foreseen and prevented. And its effects could have been mitigated by a more effective human response. (ReliefWeb, 2012)

Safety

Those accidents highlight two issues: keeping reactors cooled, and the role of human operators.

Designers have taken the cooling issue to heart. Taking advantage of the lower power levels of SMRs, they have focused heavily on gravity-based passive cooling measures. In contrast to the failed cooling systems whose shutdown caused previous accidents, gravity-based designs are particularly effective in dealing with loss-of-coolant events and station blackouts, because gravity, which drives convection, never turns off. Each proposed design must be analyzed carefully. But one could reasonably conclude that SMRs can be built that will automatically shut down without operator intervention. This is the case with the NuScale SMR and other designs described in Chapter 3.

Reducing risks related to human operators is challenging. At the extreme level, some designs—the Copenhagen waste burner was mentioned in Chapter

3—envisage no controls for an operator beyond one SCRAM button. Computers run everything. This is quite a change in thinking. But it is quite clear that capabilities of computers today far, far exceed those that were available in the 1960s and 70s, when reactor control designs were first being formulated. Computers fly astronauts into space, fly many commercial airliners, and, many believe, would drive automobiles more safely than humans. Lurking behind this vision is that humans with frailties are designing these systems. We take no position on this except to say that a clean slate of SMR designs presents an opportunity to explore new ways of approaching control and safety issues that significantly reduce the chances for human error.

Proliferation

The use of SMRs could potentially be limited because of concerns about greater, more widespread access to the materials used in nuclear weapons, uranium and plutonium. First, high-assay low-enriched uranium (HALEU; enriched between 5% and 20%) is a feature of many SMR designs, often at levels well above current PWR fuel assemblies. One could argue that SMRs provide greater access to HALEU by bad actors intending to make weapons. Second, SMRs will produce plutonium just as traditional (conventional, large-scale) power reactors do. But SMRs are more widely dispersed than conventional reactors and could make it more difficult to track nuclear materials produced from them.

The potential increased access to uranium appears to be the lesser problem. Realistically, further enrichment is needed to make a weapon, and that entails special facilities to first convert the uranium oxide to uranium fluoride. Further purpose-built facilities would be needed to centrifuge the fluorides to separate the U-235 from the U-238. This would have to be done repeatedly to get a high fraction of the U-235. While not impossible, it is dauntingly impractical. If a nation-state already has that (secret) capability, it can enrich from natural uranium to begin with. This will take longer, of course, and require more energy than enriching from 20% HALEU. But there doesn't seem to be a decisive time or energy saving by intercepting HALEU fuel. The one concern here is that an enrichment facility using HALEU feedstock will be smaller and easier to conceal than a facility starting with natural uranium. National and international agencies will need to pay close attention to enrichment facilities feeding SMRs. The Union of Concerned Scientists report has several recommendations on this point (Lyman, 2021).

Access to plutonium is more problematic. A plutonium production reactor generates as much power as an SMR. A 40-MWt heavy-water moderated reactor fueled with natural uranium produces about 10 kg of weapons-grade plutonium in a year. The chemical process for separating Pu from U is well understood, albeit greatly complicated by the need for remote handling due to the intense radioactivity of a fuel assembly. An alternative technique, pyro processing, is more recent. The Union of Concerned Scientists report worries more about pyro processing, because such a facility would be much smaller than a conventional plutonium separation plant and therefore harder to detect.

The underlying theme in preventing proliferation of nuclear weapons has always been detection of enrichment facilities. The US nuclear treaty with Iran included agreements to inspect facilities. SMRs, due in part to their highly distributed nature, could well make the job of tracking material flows harder.

Reprocessing Spent Fuel

Spent nuclear fuel (SNF) has substantial recoverable fuel. This can be produced through reprocessing, as done in France at scale. However, the United States does not reprocess used fuel. One of the products of reprocessing is plutonium. In principle, plutonium is a valuable resource. One metric ton can provide 1000 MW of electricity for a year. The short answer to the US position is that it did reprocess SNF up until the time India exploded a plutonium weapon (in 1974) reportedly using reprocessing technology imported from the United States (Fetter & van Hippel, 2005). The United States prohibited domestic reprocessing following an executive order by President Carter in 1977. Prior to that, in late 1976, President Ford had ordered cessation of a domestic reprocessing facility under construction. Later administrations lifted the prohibition against domestic use of the technology, but none took up the option, because of the higher cost of reprocessing compared to that of storage and because the military already had sufficient plutonium stocked. Currently, France operates a huge reprocessing facility in Cap La Hague. It accepts SNF from across the world. The plutonium is converted to produce mixed oxide fuel for its own reactors.

Tracking illicit plutonium production has been a challenge for the IAEA for many years. The motivation for this has been the concern about its use by terrorists for weaponry. Regular on-site inspections of reactors can follow the history of fuel assemblies, but a loss of *continuity of knowledge* can occur if inspections are interrupted at the time of a fueling cycle. A running reactor gives no simple on-site indication of the fuel content (neutrinos may be an exception to this, see the following box), and measures of the content of spent nuclear fuel (SNF) are limited to estimates of the total energy in the pool. This, in principle, correlates with the initial fuel loading and burnup. It is a relatively crude measure, however, and gives no insight into the specific Pu or U content.

Neutrinos Detected to Monitor Reactors

Nuclear reactors are intense emitters of neutrinos, typically six per fission event. They are extremely hard to detect. Wolfgang Pauli, who posited the existence of the particle in 1930, famously later said "I have done a terrible thing. I have postulated a particle that cannot be detected." He was wrong, though. Construction of huge multi-ton liquid scintillator detectors has enabled reactor neutrinos to be detected up to 100 km away. Differences in the neutrino energy spectra between plutonium and uranium stimulate intense research into the possibility of remote monitoring of reactors (Bernstein et al., 2020).

On the positive side, many SMRs have long fuel cycle times, some up to decades between fuel rod replacements, which would make the plutonium much less accessible. It is locked up inside the reactor itself, not in SNF rods in an outside cooling pond. And if the whole reactor is swapped out and returned to the manufacturer, as could be the case with SMRs, responsibilities are clearer, and tracking and accounting potentially become more manageable.

Waste Disposal

Classifying SNF as waste is something of a misnomer, as it still contains 90% of its potential energy in the form of fissionable actinides like plutonium and other heavy elements ($Z = 89$ to 103). If not for these actinides, the intense radioactivity (which is primarily due to the products of fission, such as Cs-137 and Sr-90) would be gone after some hundreds of years. Fuel reprocessing is a way to recover a good part of this energy. The United States has not pursued that strategy for commercial reactor SNF, focusing instead on disposal. Without much success, it must be said. The proposed disposal site at Yucca Mountain in Nevada has been contested for decades by members of Congress and is not close to opening. At present, SNF is stored mostly where it is produced, at 76 reactor locations in 34 states, according to the US Department of Energy.

Only one country, Finland, has made any progress toward establishing a disposal repository for civilian nuclear waste. The Onkalo site consists of a network of tunnels 450 m under bedrock and is scheduled to start receiving waste sometime in the 2020s.

We do not discuss US defense reactor waste here. For more on that, and particularly on the Waste Isolation Pilot Plant in New Mexico, see the recent study by the US National Academies of Science, Engineering, and Medicine (2020).

Although progress on disposal is disappointingly slow, it's worth remembering that the amount of SNF from the US commercial reactor fleet is not great. The total since the 1950s is supposedly 83,000 metric tons (currently 2,000 per year), and all of that would fit on a US football or soccer field stacked 3 m high. That cannot be done, of course; the fuel rods would go critical. Storage sites keep the fuel rods separated and surrounded by neutron absorbers, such as boron. But the volume is modest and could even be much less if the fuel were reprocessed to separate the long-lived actinides from the shorter-lived fission products.

Would any of these disposal issues be different with SMRs? Given lower power levels, the SNF could perhaps go to appropriately controlled dry storage facilities operated by the manufacturer instead of expensive and worrisome wet storage facilities. A secure controlled environment is still required. In one study (Krall et al., 2022), the authors argued that SMRs would exacerbate the challenges of long-term waste management, in part because the smaller size would lead to more activation of structural materials compared to a standard PWR. This is plausible, but the volumes are still modest. The challenging part of waste disposal continues to be the SNF, which is dependent solely on the number of fission events and not on the reactor size.

More interesting is the option to use SMRs to burn the waste as fuel, accessing the 90% unused energy. Several designs address this application.

"Burn the waste" is a catchy phrase, hiding myriad details, problems, risks, and costs. The Union of Concerned Scientists report has much to say on this topic (Lyman, 2021). Citing *generational equity*, it argues that there is no way of avoiding construction of a multi-thousand-year geological storage facility for SNF. There's no clear solution here. Which is unfortunate, because this is the first time a new disposal option (i.e., SMRs) has come along to address an issue that has been a drag on nuclear power for decades.

In summary, SMR developers have endeavored to address concerns of both the technical and lay publics regarding nuclear energy. On safety, the designs have emphasized passive control, meaning control of potentially catastrophic events not requiring external action or power. Some may call it intrinsic safety. The handling of SNF is largely addressed by the volumes being smaller and the duration between fuel rod replacements being as much as decades. Preventing proliferation is primarily addressed through better SNF handling and fuel monitoring. Were thorium-based reactors to become popular, the absence of plutonium in the fission products would directly address the proliferation issue. Countries such as India, with a lot more domestic thorium than uranium, may well choose to go that route. SMRs do not obviate the need to develop long-term geological storage capabilities. Finally, while *innovative* and *advanced* are appealing labels, evolutionary improvements often lead to the best long-term and cost-effective outcomes for technologies (cf., the internal combustion engine). In this regard, only the PWR-based concepts can fully lay claim to be building on decades of real-world experience.

References

Bernstein, A., Bowden, N., Goldblum, B. L., Huber, P., Jovanovic, I., & Mattingly, J. (2020). Colloquium: Neutrino detectors as tools for nuclear security reviews of modern physics. *Review of Modern Physics, 92*, 011003. https://doi.org/10.1103/RevModPhys.92.011003

De Geer, L.-E., Persson, C., & Rodhe, H. (2018). A nuclear jet at Chernobyl around 21:23:45 UTC on April 25, 1986. *Nuclear Technology*, *201*(1), 11–22. https://doi.org/10.1080/00295450.2017.1384269

Fetter, S and van Hippel, F. N. (2005, September 1). Is US reprocessing worth the risk? *Arms Control Today*.

Krall, L. M., McFarlane, A. M., & Ewing, C.R (2022). Nuclear waste from small modular reactors. *Proceedings of the National Academies of Science, 119*(23), e2111833119.

Lyman, E (2021) *"Advanced" isn't always better: Assessing the safety, security, and environmental impacts of non-light-water nuclear reactors*. Union of Concerned Scientists. https://www.ucsusa.org/resources/advanced-isnt-always-better

National Academies of Science, Engineering, and Medicine. (2020). *Review of the Department of Energy's plans for disposal of surplus plutonium in the waste isolation pilot plant*. National Academies Press

ReliefWeb. (2012). The official report of The Fukushima Nuclear Accident Independent Investigation Commission, the official report https://reliefweb.int/report/japan/official-report-fukushima-nuclear-accident-independent-investigation-commission

World Nuclear Association. (2022). *Chernobyl accident 1986*. https://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/chernobyl-accident.aspx

Societal Concerns Over Nuclear Energy

Introduction

The public views nuclear energy as risky, and this topic is widely considered polarizing and divisive (Ho et al., 2019). The views of the public regarding nuclear energy are likely to be colored by their knowledge of nuclear energy as a weapon of destruction and by the memory of nuclear reactor accidents. A recent study, using randomized control methods that infer causality without confounding factors, concluded that concerns about military and civilian nuclear use were strongly correlated (Baron & Herzog, 2020). In this chapter, we explore the areas of concern and the measures the small modular reactor (SMR) industry might take to get acceptance. For evidence that this is possible, one needs to look no further than the nation of France, where over 70% of electricity is produced by nuclear reactors. While surveys indicate high percentages of approval in countries such as the United States, the response is pronounced in being opposed when either the civilian or military nuclear facility is nearby (Baron & Herzog, 2020). In France, this sentiment must have been overcome for such a proliferation of nuclear power to have occurred. At the risk of oversimplification, public sentiment boils down to the perception of risk associated with nuclear energy.

Risk could be broadly defined as the likelihood that a given set of human actions would result in outcomes that deteriorate conditions that a person values. These conditions could cover a broad swath to include privation suffered by individuals, environmental degradation, and impact on ways of life. All forms of energy have associated risks. Since energy is important to ways of life, and plentiful affordable energy is possibly the single greatest determinant of prosperity, risks are more likely to be tolerated. Yet, given a choice in energy, the public is likely to pick a combination of low cost and low risk to ways of life. For reasons that are scattered throughout this book, and are discussed in some detail in this chapter, nuclear energy may be in a class by itself in its difficulty of acceptance by the lay public.

Risks are in the eyes of the beholders. In most cases, surveys have shown that experts consistently rate the risks lower than do the lay public. This is notably the case for nuclear energy, as shown in Table 5.1. In the scoring system, the highest risk has the lowest numbers. Whereas experts see nuclear as ranking 20th, two other classes of voters perceive it as number one. Vehicular risks tend to be more consistent between groups. Smoking is uniform as well, but experts consider surgery high risk.

One might be tempted to hypothesize that the disparity between experts and laypersons is due to the concept of information asymmetry (Akerlof, 1970). The extremely abbreviated explanation of this 2001 Nobel Prize winning idea might be best explained using the example of the sale of a used car. If the seller reveals all details of maintenance and so forth, the prospective buyer is more likely to view the value as higher. The opposite holds when the information is either not provided or not understood. In context, our transaction is the "sale" to the public of the value of nuclear energy as a carbon-free source of energy.

While information asymmetry is in play in many transactions, it is not so much in societal belief on nuclear energy. Interestingly, industry dogma has been to address the asymmetry. According to several investigators, that has simply not worked (Abdulla et al., 2019). The approach has worked, up to a point, in other controversial issues such as the risks with hydraulic fracturing. But given that the disparity between experts and the lay public is the greatest

Table 5.1 Ordering of perceived risks from activities and technologies

Activity or technology	League of Women Voters	Active college students	Club members	Experts
Nuclear power	1	1	8	20
Motor vehicles	2	5	3	1
Handguns	3	2	1	4
Smoking	4	3	4	2
Motorcycles	5	6	2	6
Alcoholic beverages	6	7	5	3
General (private) aviation	7	15	11	12
Police work	8	8	7	17
Pesticides	9	4	15	8
Surgery	10	11	9	5
Fire fighting	11	10	6	18

Source: Parkins & Haluza-DeLay (2011), quoting Slovic (1987).

with nuclear energy, assurance of societal acceptance may well require innovative methodology.

Dread

This is defined as great fear or apprehension. It is often associated with a visceral reaction rather than a reasoned one. These reactions may be premised upon singular events of horror. Following the 9/11 terrorist attacks, millions of people chose to drive rather than fly (Jason, 2011), despite clear statistics to demonstrate that, absent a rare event, such as the 9/11 atrocity, flying was a good deal safer than driving. Using statistics related to flying and driving, a study showed that in the 3 months following the event, more people died in automobile accidents than did in the planes involved in the attack (Gigerenzer, 2004).

Closer to our topic are the nuclear plant accidents at Three Mile Island in 1979 and Fukushima Daiichi in 2011. As noted in Chapter 4, the Fukushima accident was precipitated by an earthquake-induced tsunami. The plant easily withstood the earthquake, but the tsunami flooded the basement where the backup generators were located, and the resulting power failure caused loss of control. Neither event had associated fatalities, although many people were displaced, possibly as a precaution. Radiation sickness was a concern that did not materialize. Yet, Germany and Switzerland essentially shut down nuclear power, initially by not issuing new permits and later by not allowing re-permitting of older plants. Both countries have zero possibility of tsunamis, and the facts support the design ruggedness of the Fukushima reactors with respect to other natural events. The reasons were either dread or political expediency. More on the latter later in the chapter.

A recent study was conducted to elicit the effect of dread on energy choice (Abdulla et al., 2019). The experimental economics methods employed here have become more commonplace recently after the Nobel Prizes in Economics to Daniel Kahneman (in 2002) and Richard Thaler (in 2017), both in the field of behavioral economics, which employs such methods. Twelve hundred US subjects were asked to design an energy portfolio minimizing carbon emissions. Of the two groups, one was exposed to the data by labels (solar, wind, nuclear, etc.) and the other by environmental and accidental risk for each technology. Both groups were provided the mortality figures from the worst accidents in each genre. The group that was shown the names of the energy sources consistently chose portfolios with up to 40% lower nuclear energy content. Since both groups were looking at the same statistical data, the authors concluded that the bias against nuclear energy was based on dread. The authors suggest that improvements to the safety of newer versions of nuclear energy are necessary but will not be sufficient. A stab at sufficiency would require careful and deliberate stakeholder engagement. They opine that if the gulf between actual and perceived risk widens, policy measures may be needed to right the ship early before the opinions harden to a point of no return (Abdulla et al., 2019).

Few issues inspire dread more than radioactivity (Tynan & Abdulla, 2020). Had there been no atomic bomb on Hiroshima, and the associated imagery of death and disease, perhaps this would be less the case. Certainly, the issue of nuclear proliferation falls in this category, although this may be more in keeping with country government thinking than that of the lay public, which would not have a feel for the risks of fissionable material falling into the wrong hands. But the lay public is certainly concerned when that proliferation extends to *dirty bombs*, which are in the public eye because of extensive reporting when terrorists deploy such weapons.

Trust

One view is that acceptance will be either technology based or trust based (Golay, 2001). Technology-based acceptance is where the public forms an opinion from being told the details of the safety of the technology. This falls squarely in the belief of industry that bridging the information asymmetry is the way to go. “If they only understood what we know” is the tenet. Town hall meetings and so forth. But since this is the most commonplace means used, the wide disparity between experts and the public indicates that this avenue is far from successful (Tynan & Abdulla, 2020).

Trust-based acceptance is the faith in the opinions or actions of people in potentially risky situations (Das & Teng, 2001). This trust covers the ground of competence, perceived integrity, and the track record of performance of the technology. Competence is the ability to perform the intended task. Integrity, on the other hand, is the intent to follow the agreed-to task, by otherwise competent folks, even in the face of difficulties such as financial hurdles. This is sometimes referred to as goodwill trust (Xiao et al., 2017). Track record needs no explanation; no community wants unproven enterprises, especially in risky arenas. Nobody wants to be first. The characterization guinea pig comes to mind. The nuclear industry even has an acronym for such an emplacement, the first-of-a-kind (FOAK) reactor. Predictably (for engineers doing the nomenclature), subsequent ones are *n*th-of-a-kind (NOAKs). The *n* is an integer even during seemingly interminable construction delays, which is the hallmark of nuclear power construction.

The public must rely on two sets of players: the industry actors and the regulators who watch over them. Failures are laid at the door of one or the other of these entities, and trust erodes. France is singular in being the only European country in which the populace is supportive of nuclear energy. While polls show numbers on acceptance to be very similar in France and several neighboring countries, France is the only one where widespread use has not led to pushback from the communities. Polls are notorious for bias (hence the invention of methods such as conjoint analyses), but it is hard to argue that execution with minimal resistance is a good measure of public acceptance.

Energy security appears to have been a factor as well in France and became a priority after the Arab Oil Embargo of 1973. But the key point is that trust vested in the regulators and operators is high, resulting in a continent-leading 70% of electricity generated from nuclear power. France is also the low-cost leader and the biggest exporter. Ironically, some of that export is to Germany, which has essentially banned nuclear power following the Fukushima disaster.

Much of the German antipathy to nuclear power is grounded in politics, as is evident in the opposition by groups such as the World Wide Fund for Nature to a European Union designation of nuclear as a *transitional sustainable investment* (Pronczuk, 2022). At the time of the 2012 legislation, the left-leaning Green Party was firmly opposed, and Chancellor Angela Merkel, in this era of coalition governance, had no choice but to buckle and ban nuclear. Most left-leaning people are opposed to nuclear energy (Baron & Herzog, 2020), although that could change if it is seen as the primary foil for carbon mitigation.

In the United States, the historical reason for opposition is more than likely the military origins of nuclear fission, beginning with the atomic bomb. When the technology moved into other military endeavors, beginning with the nuclear submarine *Nautilus,* it carried the imprimatur of the industry in support of things military. This compendium of companies came to be known as the military–industrial complex. General Dynamics was a major supplier to the nuclear navy and would likely have carried that label. In any event, opposition to nuclear energy by the left is at least explainable. The transfer of thinking from military to civilian nuclear has been shown in a recent study (Baron & Herzog, 2020). The underlying basis probably centers on trust, or lack thereof in this case.

Air traffic is an interesting case of public trust collectively in the manufacturers of the aircraft, the regulators, and the pilots. Even notorious crashes attributed to design failures, such as the Airbus crash in the Atlantic off Brazil attributed by many to frozen pitot tubes (air pressure indicators estimating air speed) and the infamous failures with the Boeing 737 MAX, failed to dissuade the flying public. (One of us, VR, used to examine the face plates on the door jambs of aircraft to determine their age; then they were removed and probably placed in the undercarriage.) This underlines the staying power of trust, much as is the case with brand loyalty. The Coca-Cola Company survived the epic failure of New Coke because, upon recognizing their error, they went back to the old formula, but, importantly, named it Coke Classic, reminding the public of their love for the original. Brand loyalty just needs an excuse to reassert itself.

Increasing Societal Acceptance

Assuming that trust is the most important consideration in the perception of benefit, and that it is a key component of estimation of risk (Ho et al., 2019), this chapter will explore how that could be achieved with SMRs. We will key primarily on three measures: competence, integrity, and track record.

One competence-based approach suggests that governments set up research parks enabled to test any concept, under strict supervision (MIT, 2018). An agnostic determination could then be made between competing systems. The authors believe that a technology thus ratified would pass muster with the public on competence, but that would depend upon the country and the trust placed in the leadership.

Along similar lines is the US$140 million FORGE geothermal project. Not just a test bed for concepts, it is a place for verification and development of concepts essential to the success of geothermal energy production. The similarities with the MIT suggestion are that it is government funded and reasonably agnostic about the method used to extract the heat. But crucially, it is in an area of endeavor that does not carry a stigma with the public, and so is more likely to enjoy trust.

In contrast, we suggest an avenue squarely in the private sector, whether government supported in some way or not: power for data centers. These energy hogs are in the hands of corporations keen to be green, including Google and Microsoft. And SMRs are uniquely suited for this application.

SMRs in the Greening of Data Centers

Data centers are facilities that handle and store data. They can be essential to enterprises and continue to grow in importance as businesses increasingly rely on computed information for their decisions. They could be characterized as the brains of the internet, especially the cloud version. The primary difference between cloud operations and those of data centers is in remoteness. Cloud storage and computation may be accessed only on the internet. Data centers, on the other hand, are captive and can be connected directly to the user. But in energy usage they are about the same.

The Revenge of the Mainframe

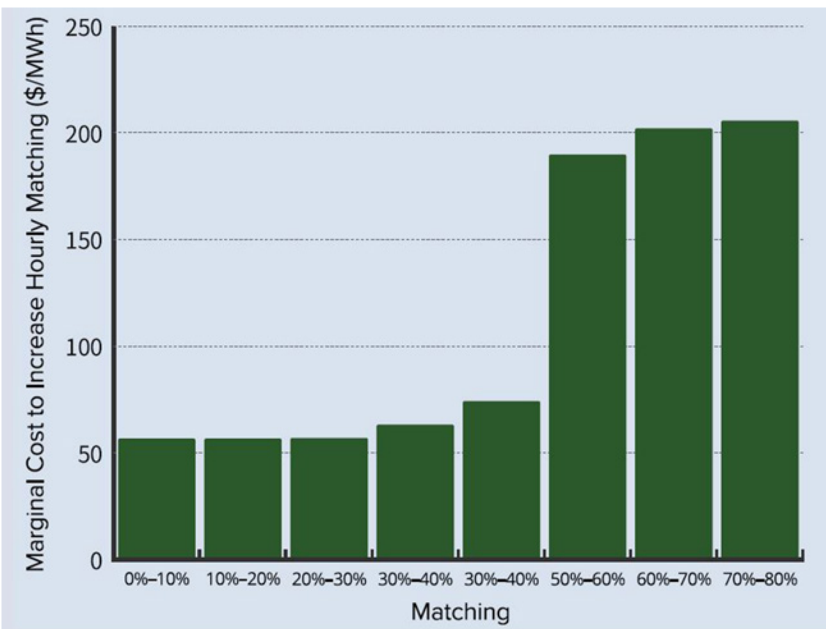
Someone once referred to the cloud as the revenge of the mainframe. This alludes to the fact that computers began as clunky assemblages, known as mainframes, occupying considerable space. This phase was followed by minicomputers, which performed similar functions in smaller space. Eventually, personal computing became the province of personal computers, or PCs. Compute functions and storage were on the PCs, and processor speeds became faster to enable this. Mainframes disappeared from offices. Then, the internet and the explosion in computer-generated data and associated decisions caused the creation of data centers and their country cousin, the cloud. These were essentially mainframes in groups, hence the allusion to revenge over the PCs that ousted them.

These things are essentially buildings with linked computers and storage devices. Therein lies the problem. Many servers, in close proximity, operating almost continuously, generate a great deal of heat and consume copious amounts of energy. The energy to run them and keep them cool has resulted in data centers as a class being one of the prime users of energy. In 2010, this application used 194 terawatt hours (TWh), which comprised about 1% of energy used in the world and more than the energy usage of countries on the scale of Iran. Usage continued to explode. Extrapolative predictions were dire. Yet, in 2018 the usage was 205 TWh, a mere 6% increase, despite the fact that compute instances increased by 550% (Masanet et al., 2020). This again was close to 1% of world electricity usage.

The increase in energy efficiency over that 8-year period was an order of magnitude better than the efforts of the air transport industry, that other difficult-to-decarbonize industry. Computer efficiency of the data center assemblies was improved, as was the storage efficiency. While these efforts continue, they may not keep up with the continued growth in the market. This increases the imperative for the electricity to be derived from low- or zero-carbon sources, such as SMRs and advanced geothermal systems. They are at the right scale and are expected to deliver at comparable costs.

The traditional renewables are not well suited to the data center application. This is best exemplified by Figure 5.1.

Figure 5.1 Marginal cost for matching data center loading with renewables



Source: Rocky Mountain Institute (Dyson et al., 2021). Used under a Creative Commons BY-SA 4.0 license (https://creativecommons.org/licenses/by-sa/4.0/).

These are estimates of supplying renewable energy to a data center in the PJM Grid system in the US northeast, one of many grids used as examples in the report. The continuous energy need causes the solar- and wind-based relatively low-cost supply to be inadequate after about the 50% point. The costs thereafter are for battery-supplied power. The key takeaway is that a carbon-free alternative need not match solar and wind numbers. It simply needs to be comparable to batteries, the current carbon-free supply augmenter. NuScale estimates come in at US$65, well below the large bars of battery power.

This entire section was intended to give the example of data centers as needing 24/7 energy supply, making them unsuited to conventional renewable energy systems. Consequently, they are perfect test beds for a near-zero-carbon source, such as SMRs. Add to that the stated intent of the key data center players, such as Google and Microsoft (Microsoft, 2019), to be carbon free at these centers by specified dates as early as 2030, and we have a recipe for rapid deployment. Importantly, safe and effective deployment by actors seen by the public as competent, with track records of delivery of new and complex systems, could well increase the trust in the systems. These entities are likely to want to promulgate their success, and as they are particularly skilled at social media communication, the result could be an uptick in societal acceptance.

SMRs Enabling Lower-Carbon Heavy Oil Production

This is another example of a technologically appropriate use of SMRs where safe operation could be demonstrated to bolster public trust. The carbon footprint of heavy oil operations in Canada and elsewhere is very high for two reasons. One is that the oil is too viscous to be pumped out of the reservoir without heating, and the heat is supplied in the form of injected steam, the production of which emits CO_2. The process of oil extraction is known as steam-assisted gravity drainage (SAGD). The second reason is that the oil has a high proportion of long-chain molecules, and converting it to usable fuel, such as gasoline, requires operations that crack these molecules. Aside from energy usage, cracking requires hydrogen, because the lighter molecules, such as gasoline, have a higher hydrogen-to-carbon ratio than does the heavy crude.

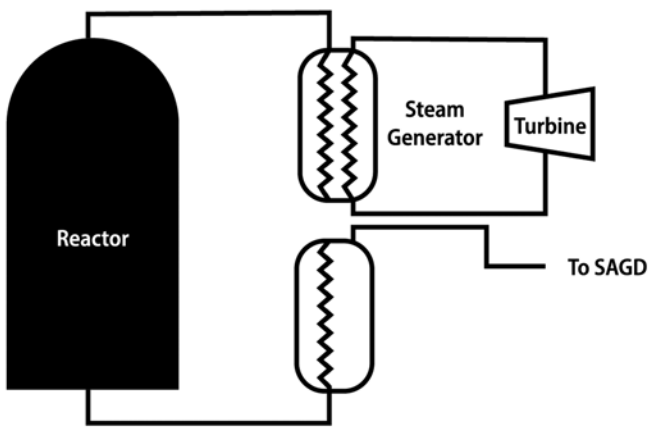
SAGD processes vary in the amount of steam used, dictated by factors such as reservoir quality and depth. A reasonable figure for emissions appears to be 110 kg CO_2 per barrel of oil produced (Donev et al., 2018). With Canadian production at about 1.3 million barrels per day, the CO_2 emitted is 52 million metric tons per year. Nearly all of this could be eliminated if steam generation from natural gas were to be replaced by steam from SMRs. Figure 5.2 is a schematic for one possible architecture.

In this variant, the SMR output would be split to produce steam to both drive turbines and feed the SAGD wells. The wells require temperatures in excess of 250°C and steam quality (percentage of steam in the fluid) of 90% plus. This is achievable by many SMRs.

The sizes of the SAGD production fields vary. They tend to be in the range of 30,000 to 50,000 barrels per day (bpd). But 100,000 bpd fields also exist, and we will do a rough computation. For a field of this size, an average of about 1000 MWth (megawatts thermal) would be required, based on a steam-to-oil ratio (barrels of steam per barrel of oil produced) of about 2.5 (Becerra et al., 2005). For many SMRs, this quantity would be produced by a plant sized at about 350 MWe. Depending on electricity needed by the plant or surrounding community, the reactor would be larger. But, on steam alone, the size is about four or five NuScale units in combination. Interestingly, this is about half the number of the units required to repurpose retired coal generating plants (see Chapter 8). There is an analog here, in a sense, because in this case we are retiring the natural gas steam generation system and repurposing it with a nuclear one, keeping the distribution hardware intact.

The cost comparison for this replacement will depend heavily on the cost and availability of natural gas. Availability is not much of an issue in western

Figure 5.2 Schematic of SMR supplying steam and electricity for SAGD



Canada. But at a cost in the vicinity of US$5 per MMBTU, and any reasonable price on carbon, the substitution could be expected to be a net economic positive.

Noted earlier was the fact that heavy oil needs hydrogen supplements to convert to useful fuels. If the price were right, a portion of the nuclear output could be spent in producing electrolytic hydrogen. It could be shipped to the upgrader facility and replace hydrogen from natural gas, making the product greener still.

The public is likely to view the SAGD application favorably primarily because it has been safely executed by an industry known to face hazards in operations. It is also an industry which has over five decades of experience with the storage, transport, and utilization of radioactive materials. Additionally, the displacement of a high-carbon footprint technology would find favor with environmentalists, who as a class tend to be opposed to nuclear energy. A study showed that respondents most favoring environmental regulations were much more likely to view nuclear technology negatively (Baron & Herzog, 2020). A recent decision by the European Union to declare nuclear a *sustainable investment* area has been strongly criticized by European environmental groups (Pronczuk, 2022).

A personal note (from VR). The box in Chapter 3 recounts a story of an early SMR. At the time I was introduced to it, I was thinking about exactly this application, in heavy oil fields. Some years later, I co-invented a scheme to produce the steam downhole, which made the efficiency higher, but also the CO_2 simply went into the reservoir (Iqbal et al., 2009). It had other novel features, but never took off. So, when Los Alamos scientists came to see me about their new SMR, the application was on my mind, and I wanted to take it to Canada. My chief physicist had blessed the science. But I had trouble getting support from upper management because of the expected hurdles in acceptance by the public. Perhaps we dodged one (see the story in the Chapter 3 box) or perhaps we, as a major corporation championing it, may have made it take off. We will never know.

Like all nuclear power, SMRs face a battle for societal acceptance. The public experiences dread and lacks trust in these technologies due to concerns about accidents, misuse in bombs, and the challenges of long-term storage. More information has not proven a viable strategy for increasing societal acceptance. We suggest instead that incorporation and competent operation of SMRs in energy-intensive applications is an effective way of establishing a track record, increasing trust and, eventually, achieving acceptance.

Shooting Down Lead

This is the story of an attempt at ameliorating the legislation-induced angst of the waterfowl hunting society. I (VR) was a freshly minted PhD at the Central Research Laboratory of NL Industries. It had been called National Lead, but they took the lead out, primarily in the name. A profitable product line was lead shot. These things are spheres of a lead alloy a few millimeters in diameter. Bird shot tends to be about 3 mm and this story is about birds. Ducks, to be exact.

I was designing better shot for clients. So, I learned the main features. They needed to be round and hold a tight pattern (not flare out) upon discharge. The density of lead helped in that regard. They could not be so hard as to abrade the gun barrel. But they also needed to be hard enough to "cut feathers." The term is self-explanatory and was a desirable feature. Not so much by the fowl.

This was in the mid-1970s, and the environmental community had concluded that lead shot was bad for ducks, beyond the obvious mortality-causing propensity. Ducks pick up pebbles in water bodies and use them to grind down the food in their gullet. They are believed to do this by feel and not sight. If lead shot was around, the ducks would mistake them for pebbles and the grinding action would poison them. The shot would be present for the obvious reason that hunters miss more ducks than they hit.

The legislation being considered was to replace lead with steel shot in the flyways. Gun barrels had to be replaced to account for the more abrasive steel. The lower density meant they flared out more, and bad hunters became worse. The freshly minted PhD thought he could solve the problem.

I had been working on improved lead shot. I conceived of a formulation that would fall apart in water. Metallic lead is not soluble in fresh water, so the chunks would not contaminate the water and the ducks would not be tempted by the fragments. Before I launched a test of the product, I had a conversation with one of my sales buddies. He listened carefully.

"You are not a hunter, are you?" he asked, with this little grin, which made me wary.

"Never shot a gun in my life," I responded. By now I was on my guard.

"What do you think will happen to the pellets in the dead bird when cooked?" was his question. Grin still intact. My guard still up.

So, I was thinking furiously. I did know that pellets were never removed from the bird prior to cooking; too tedious. There it was, staring me in the face. High temperatures, natural juices, disintegrating pellets. He still had the grin.

Nothing quite like taking a PhD down a peg or two, is there?

There it was. My invention was going to reduce the population of hunters. Worse still, customers. Easing the way to societal acceptance of waterfowl protection regulation would be left to others.

References

Abdulla, A., Vaishnav, P., Sergi, B., & Victor, D. G. (2019). Limits to deployment of nuclear power for decarbonization: Insights from public opinion. *Energy Policy*, *129*, 1339–1346. https://doi.org/10.1016/j.enpol.2019.03.039

Akerlof, G.A (1970). The market for "lemons": quality uncertainty and the market mechanism. *Quarterly Journal of Economics*, *84*(3), 488–500.

Baron, J, & Herzog, S. (2020). Public opinion on nuclear energy and nuclear weapons: The attitudinal nexus in the United States. *Energy Research & Social Science*, *68*, 101567. https://doi.org/10.1016/j.erss.2020.101567

Becerra, G., Esparza, E., Finan, A., Helvenston, E., Hembrador, S., Hohnholt, K., Khan, T., Legault, D., Lyttle, M., Miu, K., Murray, C., Parmar, N., Sheppard, S., Sizer, C., Zakszewski, E., & Zeller, K. (2005). *Nuclear technology & Canadian oil sands: Integration of nuclear power with in-situ oil extraction*. Massachusetts Institute of Technology, Department of Nuclear Science and Engineering. https://web.mit.edu/kadak/www/oilsands_report.pdf

Das, T. K., & Teng, B. S. (2001). Trust, control, and risk in strategic alliances: An integrated framework. *Organization Studies*, *22*(2), 251–283. https://doi.org/10.1177/0170840601222004

Donev, J., Afework, B., Chahal, D., Hanania, J. et al. (2018). *Energy education—Steam assisted gravity drainage*. https://energyeducation.ca/encyclopedia/Steam_assisted_gravity_drainage

Dyson, M., Shah, S., & Teplin, C. (2021). Clean power by the hour: Assessing the costs and emissions impacts of hourly carbon-free energy procurement strategies. RMI. http://rmi.org/insight/clean-power-by-the-hour

Gigerenzer, G. (2004). Dread risk, September 11, and fatal traffic accidents. *Psychological Science, 15*(4), 286–287. https://doi.org/10.1111/j.0956-7976.2004.00668.x.

Golay, M. W. (2001). *On social acceptance of nuclear power.* Study for the James Baker Institute of Public Policy, Rice University.

Ho, S. S., Leong, A. D., Looi, J., Chen, L., Pang, N., & Tandoc, E. C., Jr. (2019). Science literacy or value predisposition? A meta-analysis of factors predicting public perceptions of benefits, risks, and acceptance of nuclear energy. *Environmental Communication*, *13*(4), 457–471. https://doi.org/10.1080/17524032.2017.1394891

Iqbal, R., Rao, V. & Eng, O. (2009, December 8). *Wastewater disposal with steam production*. US Patent 7,628,204.

Jason, G. (2011). Nuclear power and dread risk. *American Thinker.* https://www.americanthinker.com/articles/2011/05/nuclear_power_and_dread_risk.html

Masanet, E., Shehabi, A., Lei, N., Smith, S., & Koomey, J. (2020). Recalibrating global data center energy-use estimates. *Science*, *367*(6481), 984–986. https://doi.org/10.1126/science.aba3758

Microsoft. (2019). *Vattenfall and Microsoft pilot world's first hourly matching (24/7) of renewable energy.* https://www.microsoftpartnercommunity.com/t5/Energy/Vattenfall-and-Microsoft-pilot-world-s-first-hourly-matching-24/m-p/55033/highlight/true

Massachusetts Institute of Technology (MIT). (2018). *The future of nuclear energy in a carbon-constrained world*. Report of the MIT Energy Initiative.

Parkins, R. P., & Haluza-DeLay, R. (2011). *Social and ethical considerations of nuclear power development, staff paper.* University of Alberta.

Pronczuk, M. (2022, February 2). Europe labels nuclear and natural gas as sustainable investments. *The New York Times*. https://www.nytimes.com/2022/02/02/business/energy-environment/europe-green-taxonomy.html?searchResultPosition=1

Slovic, P. (1987). Perception of risk. *Science, 236*(4799), 280–285.

Tynan, G. R., & Abdulla, A. (2020). How might controlled fusion fit into the emerging low-carbon energy system of the mid-twenty-first century. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2184), 20200009. https://doi.org/10.1098/rsta.2020.0009

Xiao, Q, Liu, H, & Feldman, M.W. (2017). How does trust affect acceptance of a nuclear power plant (NPP): A survey among people living with Qinshan NPP in China. *PLoS ONE*, *12*(11), e0187941. https://doi.org/10.1371/journal.pone.0187941

Navigating Dunkelflaute

Introduction

In many countries, one can safely assume that when we flip a switch, the lights turn on, meaning electricity should be available, on demand, 24/7/365. That means we need a variety of electric power generation interconnected though an expansive grid that distributes electricity to where it is needed when it is needed. The challenge is maintaining a consistent supply that meets demand (load) during periods of both higher and lower consumption. The climate debate, and accelerated technological advancements, have led to an increase in electricity produced from renewable resources, and most people would equate that renewable energy with solar- and wind-derived electricity. In fact, in many jurisdictions solar and wind are *the* low-cost sources of electricity, and effectively the primary generating source.

But electricity from these sources cannot be generated when the sun doesn't shine, or the wind doesn't blow. Matching demand with generation of intermittent renewable electricity adds another level of complexity for managing supply from the grid. Dunkelflaute is the German term for a windless darkness, or more fancifully, dark doldrums, often extending over several days. The focus of this chapter is navigating these doldrums, or gaps, with clean energy solutions. In our view, the gap fillers are small modular reactors (SMRs), geothermal energy, and innovative storage means. They are not yet developed to scale and are unlikely to be for at least a decade. The exception is hydrogen, which is increasingly being considered for stored energy, but the cleanliness of the source is nuanced, as described later in this chapter. In the interim, fossil fuel combustion with carbon capture, utilization, and storage (CCUS) is the only realistic option for the long periods of doldrums. This underlines the need for rapid development and deployment of CCUS.

How Oil Companies are Responding to Renewables

In the move away from fossil fuel toward renewables, the behavior of oil companies is instructive. When Shell announced in 2021 that their oil production had (deliberately) peaked in 2019, and that they intended the declining trend to continue annually, this was a signal of anticipated demand destruction. BP had been giving similar signals. In all cases when oil companies declared intent to move away from oil and gas, solar and wind were where they headed to fill their energy portfolio. The reason for that choice could well have been that the other types of renewable energy had issues with scale and location. These would have been hydroelectricity and conventional geothermal. Nuclear energy would have occupied a middle ground of being generally accepted as carbon free but certainly not renewable. Yet, no oil company took that route. But if reducing carbon intensity is the objective, nuclear fits the bill, albeit with other baggage; but then, all forms of energy come with some baggage. SMRs now offer a more approachable nuclear alternative.

Intermittency in Solar and Wind

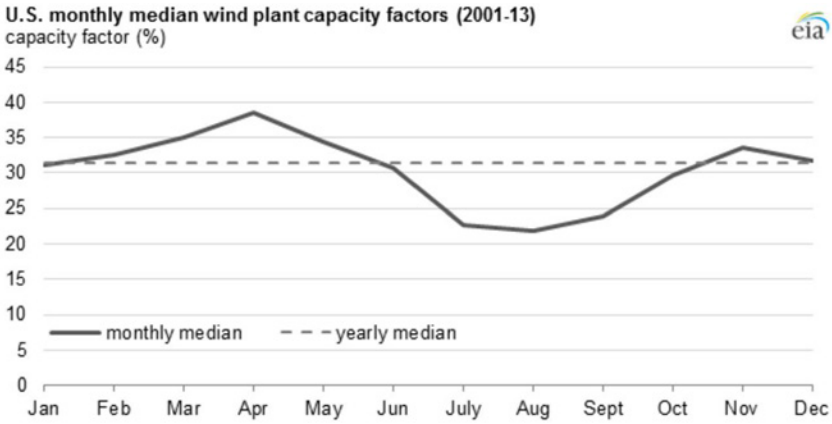
Wind capacity factors range from 25% to 45% seasonally. In the United States, except for California, which has unusual patterns, all the states follow the trajectories shown in Figure 6.1.

The peaks are in spring, and the troughs are in late summer. Summer is when the demand is high, and solar energy peaks in those months but is low in the winter and early spring. In a sense, solar and wind are complementary, and this generally applies to diurnal patterns as well.

That is in the United States. In other parts of the world, different climatic factors are in play. For example, Figure 6.2 shows the monthly pattern in southern India.

The main takeaway is that higher wind is experienced in the summer monsoon season, followed by a significant drop in winter. This graphic also underlines the variability between monsoon seasons, with two consecutive years showing dramatically different patterns, yet maintaining the general features of the season. Note also that all the numbers are lower than those in the United States, especially in the winter months. The variability day to day and year to year in the same periods underscores the need for load-following

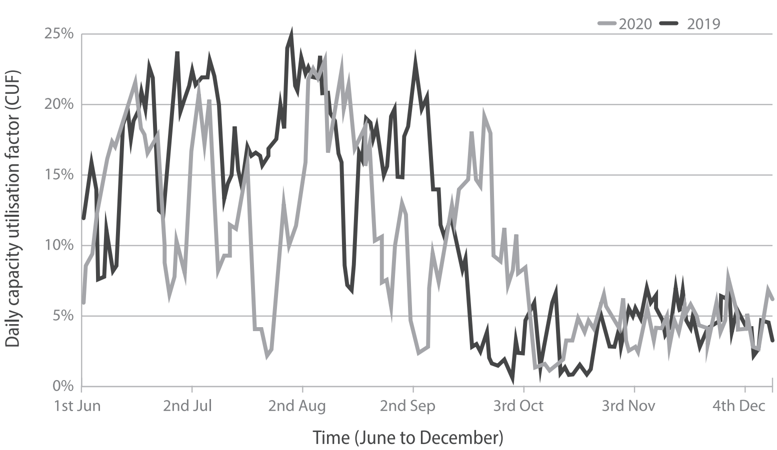
Figure 6.1 Wind capacity factor variability in the US capacity factors, 2001–2013 (%)



Source: US EIA (2015a).

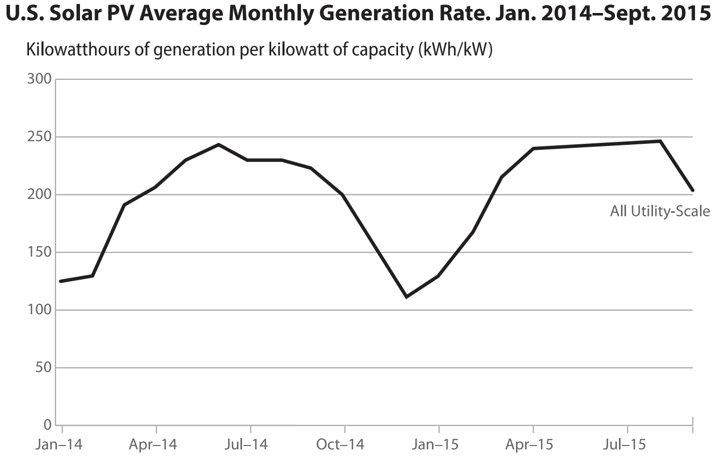
sources. Today, natural gas generation is by far the most common means for filling the gaps formed by the longer-term variability. In countries where natural gas is largely imported, such as India, one could expect biogas and coal-derived gas to make inroads. Over time, the carbon footprint of coal-derived gas could be reduced through CCUS.

Figure 6.2 Wind capacity factor variability in southern India



Source: Adapted from Shekhar et al. (2021).

Figure 6.3 US monthly solar photovoltaic generation



Note: US solar photovoltaic month generation rate, January 2014–September 2015, in kilowatt-hours of generation per kilowatt of capacity.
Source: Adapted from US EIA (2015b), *Electric Power Monthly*, Table 1.1A, 1.2C–E, 6.2B.

Short-term backup of less than 6 hours is largely achieved with batteries. This is expected to continue, although the drop in the cost of lithium-ion batteries is unlikely to continue apace with the last decadal drop. Other chemistries are being researched and will make inroads in these stationary applications where the lithium premium of lightness is not a factor.

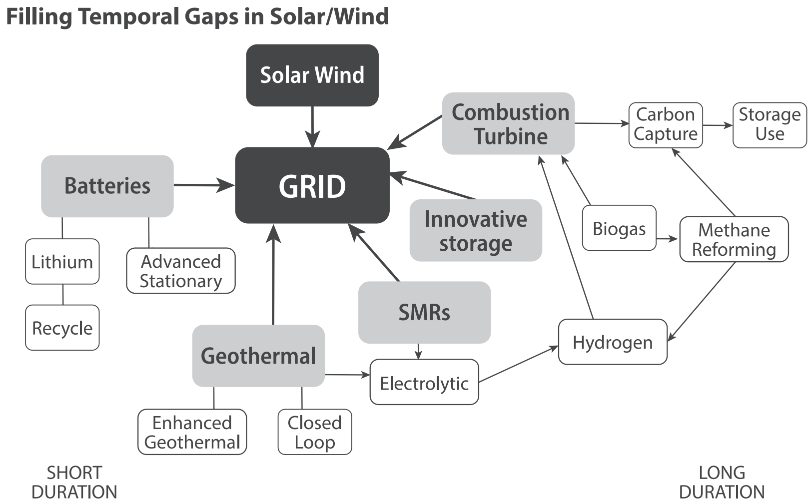
Solar energy too has seasonal variability, largely due to changes in average daylight hours. Figure 6.3 shows a typical pattern in the United States over 2 years.

The sharp dips in January correspond to peak wind resources. While these offsets exist in grid systems with both sources of energy, the daily variability with solar is severe in not covering the 4 to 6 hours in the early evening, which tend to be high load periods. These are being handled by batteries today and will probably continue to be so.

Alternatives for Augmenting Solar and Wind

The list of low- to no-carbon electricity augmentation to complement solar and wind is short. It can be broken down into two classes: short-term, defined by less than 10 hours, and long-term. Short-term augmentation is dominated by batteries, and that is unlikely to change. The cost of lithium-ion batteries has plummeted by nearly a factor of 9 in a scant decade (Statista, 2022).

Figure 6.4 Alternatives in short- and long-term augmentation of solar and wind output



Alternative chemistries are being pursued, in part because stationary applications such as these do not need the lightweight advantage of lithium. Furthermore, lithium supply is an issue, with the bulk of it coming from South America (Schwager 2021). Recycling of lithium and cobalt will be priorities to prevent the few suppliers from emulating oil cartels in manipulating price.

Mind maps are a visual representation of the various elements contributing to a solution. Connections between elements, including interdependencies, can be seen in a single pictorial representation. The mind map in Figure 6.4 illustrates the alternatives for filling the gaps in solar and wind supply to the grid, in both the short- and long-term spaces. Solar and wind are increasingly occupying the low-cost position in all sources of energy, not just the clean ones. They are already cheaper than most conventional sources (US Department of Energy, 2021). They cost less than natural gas-based generation even in countries such as the United States where natural gas prices are low. But they suffer from low capacity factors dictated by diurnality and seasonal variability. Corporations and communities targeting 100% renewable energy will consider solar and wind to be their base load when augmented by other sources. Other sources broadly fall into three categories: generation with load-following ability, combustion generation, and innovative long-term storage. SMRs and geothermal energy are in the first category. Expect one or both to dominate 15 years out. But the interim needs to be served to keep growing solar and wind. That is where the second category comes in. This category too may continue to be a part of the mix, and almost certainly will, if for no other reason than amortization of capital already expended.

Generation with Load Following

Load-following base-load type generation will inevitably have idle periods. These are periods during which the solar and wind supply matches demand and does not need augmentation. One solution is to not idle, but instead put that electricity to work to produce hydrogen from electrolysis of water, the uses for which could include combustion for power. Of course, the problem of capital utilization now shifts to the electrolyzer, because it will be operated for only those limited hours of solar and wind self-sufficiency.

Combustion Generation

Combustion generators are the workhorses of plugging the gaps not filled by batteries. They are usually natural gas fired, although oil may be used when natural gas is in short supply, such as in the Great Texas Freeze (Rao, 2021). Oil substitution is possible because many of these units are dual fired. As of 2022, with unprecedentedly high natural gas prices, oil substitution is common in Europe and parts of Asia. But natural gas produces CO_2, albeit half that from coal. In the longer term, this source will be acceptable only with CCUS.

Combustion generators have a lower capital cost per installed nameplate capacity than coal, nuclear, or hydro. Accordingly, they are well suited to be gap fillers, because the penalty for lower utilization is comparatively less. Such units can achieve a low- to no-carbon status if the fuel is green. The candidates for that are electrolytic green hydrogen (or really, blue as well; see the “Shades of Green” box below), biogas, and methane from any source combined with CCUS. If the methane is from biomass, it may qualify without the capture. In countries with high growth of energy usage, such as China and India, the coal-based option will be preferred to augment biogas sources. Therefore, economic viability of CO_2 capture and disposition will need to be a priority. The good news is that the cost of point source capture (capture from individual industrial plants, such as power generators and cement plants) is approaching the “no excuses” value.

Innovative Storage Solutions

Many attempts are being made to address cost-effective storage of electricity in forms other than batteries. Battery advances are also being investigated, especially flow batteries (Spector, 2020). If any of these achieve commercial viability, they will join the current front runners of geothermal and SMRs for complementing solar and wind.

Storage solutions have been researched for years. All target periods exceed 10 days. Technical viability has largely not been an issue. The hurdle has been cost. One approach compresses air with the excess electricity and then releases it as needed to drive a generator. Compression generates heat, and this limits the degree of compression in each stage. This is also the phenomenon that limits compression ratios in gasoline engines. Multistage compression is costly. One startup has found a way to cool down the compression dynamically. Another approach stores fluid at high pressure in geologic formations and releases it as needed. Yet another lifts blocks and then drops them when needed. A German startup places a heavy weight in a shaft. Water is pumped under the weight to lift it. When the energy is to be recovered, the weight is dropped, and the water runs a turbine. All storage solutions require that the energy be generated in the first place, usually during periods of low demand. In that sense, storage solutions are not direct replacements for SMRs or geothermal, but they could be important complements. That is one reason that they are getting light treatment in this book.

Shades of Green

Remember when green was just a part of the spectrum at nominal wavelength 550 nm? Well may you yearn for those days. Now its nearest neighbor on the spectrum, blue, for ages comfortable in its nominal 450 nm skin, must be content with the consolation prize for not being green enough. Gray was always nondescript, and certainly not in the upper crust of being a pure spectrum color. But even it is deserving of more respect than it is now getting. After all, gray is in that bourgeois spirit Grey Goose. Here is the sordid tale of shades of green.

Hydrogen is now distinguished by colors. Ninety-five percent of hydrogen used industrially today is from steam methane reforming, described by the following equations:

$$CH_4 + H_2O \rightarrow CO + 3\ H_2 \qquad (6.1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (6.2)$$

The first step produces a mixture known as synthesis gas, or syngas for short. It is the basic building block of a host of chemicals, including plastics. When further reacted with water in the Water Gas Shift reaction, hydrogen and CO_2 are produced.

The common practice in industry is to release the CO_2 after separation from the hydrogen. This hydrogen has the prefix gray. If the CO_2 is captured and stored geologically or otherwise, the associated hydrogen is categorized blue.

Were the syngas to be derived from the gasification of coal, as is done routinely in China, which is not self-sufficient in natural gas, the hydrogen is labeled brown. India will also almost certainly go this route for the same reason as China. The governing equation for that reaction is

$$C + H_2O \rightarrow CO + H_2 \quad (6.3)$$

Even the modestly discerning will note that the reaction products are the same as in the natural gas reaction except for the proportions of the products. The next reaction is precisely the same. So, what gives? Why is this hydrogen brown and the other blue? One possible explanation is that per kilogram of hydrogen produced, more CO_2 is emitted in the case of coal. But if it is all sequestered, why ought that to matter? The capture is unlikely to be 100%, so the residual CO_2 would be greater per kilogram of hydrogen than in the case of the coal-based hydrogen production. But is that a hair split?

Here is another twist. If the source of methane is biogas from animal or other waste, the hydrogen is green. There may not be consensus on this point, although the government of India has put out a policy (Mehta & Shah 2022) defining this as green. The only hydrogen unanimously seen as green is from the electrolysis of water using renewable electricity. Does hydrogen produced using electricity from a zero-carbon emissions source, such as nuclear, count? Yes, but it has its own color, purple. And don't forget, Kermit the Frog once said that it is not easy being green.

Methane and Hydrogen from Biomass

Hydrogen is increasingly being considered for stored energy, but the cleanliness of the source is nuanced, as described in the box above. Biomass of commercial importance can loosely be classified as woody biomass and animal waste. The first category largely comprises forest products and so is heavy on cellulosic content. The second is dominated by swine, dairy, and poultry excretions and is more on the organic side. Each has a principal means for treatment.

Woody biomass is gasified to produce syngas, from which many products may be made. Another approach is to pyrolyze it to produce an oil-like liquid and char. Swine waste is conventionally stored in water bodies, referred to by the genteel name lagoons. Disposing of it is a challenge. It can be sprayed on fields as fertilizer, but the odor is unpleasant. Another option is anaerobic (air-free, oxygen-starved) digestion that can occur in lagoons if they are covered or in separate tanks like you might see in a wastewater treatment facility. The product from anaerobic digestion is biogas, a mixture of methane (50% to 75%) and CO_2 (25% to 50%) with some nitrogen and trace impurities of hydrogen sulfide and ammonia. If methane concentration is increased to about 95% and the impurities are removed, this renewable product can be injected into natural gas pipelines for general consumption. In some jurisdictions, there are mechanisms for obtaining renewable energy credits for using it in power plants and other applications. This could be a source of fuel for combustion generators, even when the user and producer are not in close proximity. Alternatively, the methane could be reformed to produce green hydrogen, much as is natural gas (Equation 6.1 above). In natural gas–importing countries, such as China and India, this could serve as a material source of hydrogen.

Hydrogen from either of these sources could have associated CO_2 captured and stored. But moving it great distances is costly.

State of the Art in CO_2 Capture and Storage

This is not intended to be comprehensive; that would require a slim volume. Here we describe the principal approaches and go a little more in depth into a couple of others. The intent is to investigate whether techno-economic viability is close at hand. This allows plans for bridging to the zero-carbon solutions of SMR and geothermal, which even in the most optimistic scenarios will not be at large scale until the mid to late 2030s. In the intervening decade and change, much reliance will need to be placed on economical carbon capture and storage. Considering the mind map of Figure 6.4, the entire upper right portion of augmentation of solar and wind energy is not feasible without this capability.

The first step in CCUS is capture of the CO_2. It could be at the output of an industrial source, such as electricity generation from fossil fuel. This is known as point source capture. The other broad category is capture from the air, known as direct air capture. All capture methods are more efficient if the CO_2 concentration is higher. Cement and iron and steel are the largest industrial point source contributors to CO_2 in the environment. The highest concentration is from cement plants, as much as 30%. Coal-fired power plants weigh in at about 15%, and ironmaking is in that neighborhood, albeit somewhat lower. Other industrial sources range down to the low single digits. The lowest is the concentration in air, which is a fraction of a percent (400 ppm and rising!), making direct air capture economics challenging. Current recovery costs range from US$250 to 600 per metric ton CO_2 (Rhode, 2021). To put that in perspective, point source capture best-in-class numbers are US$40, as noted below.

Capture technology falls into three broad categories, not counting innovations in allied spaces. These are absorption, adsorption, and membrane separation. Absorption is a volumetric phenomenon, whereas adsorption is dominated by surface reactions. In both cases the gas is captured by reaction and later released in concentrated form by some mechanism. Membrane separation involves use of a semi-permeable barrier that selectively separates the CO_2 from other gaseous components.

The most prevalent industrial method uses absorption of the CO_2 into an organic solvent, with subsequent release in a concentrated form. The workhorse solvent is some version of an amine. A recent improvement by RTI International comprises using a nonaqueous solution (Lail et al., 2014), which can reduce the cost by about 20%. Reaction kinetics improvement is targeted using processes such as fluidized bed reactors and rotating packed beds, which are standard chemical engineering techniques in the field of process intensification. The UK startup Carbon Clean has improved the rotating packed bed method to the point where they claim capture for under US$40 per metric ton CO_2. They are targeting further improvement down to US$30. The US Department of Energy announced the funding of a combination of the Carbon Clean and RTI Technologies to address capture from cement operations (Jackson 2021). If successful, this could lead to a glide path to CO_2 capture cost as low as US$25. This approaches what we refer to as a no-excuses number, one at which cost is no longer a barrier to point source capture. The reason for this assessment is that geologic storage is feasible for under US$10 per metric ton (Schmelz et al., 2020). Geologic storage is accomplished by pumping CO_2 into either oil or gas reservoirs from which the economically recoverable fluid has been produced, leaving open spaces for the CO_2. The other hosts for the CO_2 are reservoirs of salty water. Either of these can be on land or offshore. The former has a lower cost, as low as US$5 per metric ton CO_2 stored. So, the total cost of capture and storage is still well below current market pricing of CO_2 in Europe, where penalties for release are currently in the vicinity of US$52 per metric ton. When capture and storage can be accomplished for a price lower than the penalty, there are no excuses for not doing it.

The most preferred fate for the captured CO_2 is utilization, but the primary challenge has to do with energy balance, because CO_2 is nonreactive and thus contains no energy. Any effective utilization process cannot consume more energy than it produces. The goal involves reacting the CO_2 to produce a material with utility while minimizing energy input. This is a field unto itself. But one approach bears mention here, and that is mineralization. Generically, this involves reacting the CO_2 with a substance, resulting in a carbonate with utility. Examples include the substance being a mineral with either CaO or MgO as a constituent, resulting in production of carbonates of Ca or Mg. Either could have utility in concrete manufacture, and the latter has additional value as a soil amendment in agriculture or a flux in ironmaking. The particular allure of the utilization route is that it offers the promise of negative cost of CO_2 disposal, but the challenge is minimizing the energy input to produce the oxides (calcining the carbonates). In one approach, basaltic minerals, such as olivine, are already present as oxides (silicates, to be precise) and can be reacted with CO_2 to produce a useful carbonate (Cartier, 2022).

Geothermal Energy

This is sourced from the earth's core. The bulk of the heat moving toward the earth's crust is generated from radioactive decay of potassium, thorium, and uranium. Together, they compose the source to produce geothermal energy. Until recently, useful capture of this heat was through recovery of water occurring naturally in the subsurface, which got heated on its way up. Hot springs and geysers are natural manifestations. In areas such as Iceland and parts of California, the hot water runs turbines to produce electricity. This version of geothermal energy is labeled hydrothermal.

The more recent version drills wells into areas with hot rock, pumps a fluid down (usually water), and returns the fluid to perform work. This work is commonly the production of electricity but can also be utilization of the sensible heat for other purposes. The offerings fall into two areas, and both are still in late-stage development, with a commercial deployment by Fervo Energy planned for 2023 (Richter, 2021). One is termed enhanced geothermal systems and operates at relatively low reservoir temperatures of under about 225°C. An injector well introduces fluid into the rock, usually a horizontal well. The rock is fractured to increase permeability, although natural fractures are used to enhance the flow. The fluid is heated and flows into a producer well, usually parallel to the injector well. The hot fluid flows to the surface to generators and is later returned to the injector well. Fervo Energy, a leading proponent of this approach, is projecting near-term cost of US$75 per MWh. This is in the same range as the cost projected by the SMR-based NuScale for its first commercial offering in 2029.

The second method is a closed loop system. The injector well and producer are connected, and the fluid never enters the reservoir. Common versions of this method rely on thermal conductivity of the rock, and so the reservoir temperature needs to be higher than for enhanced geothermal systems, usually over 300°C.

Unlike hydrothermal systems, neither of these geothermal methods relies on natural subsurface sources of water. Accordingly, conditions suitable for heat extraction can be expected to be present in most parts of the world. Because the heat source is essentially inexhaustible, this source is considered renewable. It is possibly the only renewable energy other than solar and wind that is scalable. The surface footprint is small relative to solar and wind. For equivalent power output, it is about 100 times smaller than for solar, and more similar in this regard to SMRs. In Chapter 8 we discuss the repurposing of retired coal plants with SMRs. Geothermal energy ought to be able to perform in a roughly similar fashion.

The key characteristic of geothermal energy that makes it suited to filling the temporal gaps in solar and wind is the ability to load follow. Load following is an industry term for supply that matches the demand profile. Simply throttling back the injection rate can restrict supply without damaging the production mechanism. In this aspect too it is similar to SMR.

The other similarity is in the modularity. A typical well triplet of two injectors and a producer will generate about 10 MWe. A single well pad could have multiples of these, added incrementally over time as load requirements increase.

Small Modular Reactors

SMRs have characteristics that make them well suited to tackling the temporal gaps in conventional renewables. Since much of this book is devoted to SMRs, here we will touch on just a couple of points. SMR modules can be as small as 30 MWe, and even as small as 10 MWe in *nuclear battery* designs. These are described in Chapter 3. The small size, together with the capability to aggregate to a larger capacity, make them well suited to the task. The smaller units would be appropriate for renewable energy *islands* in underserved areas. The load-following characteristic is also a desirable feature. A sometimes-unappreciated feature is that, since the electrical energy is derived from a turbine, the 60 Hz AC power (US) from an SMR is an immediate match for the national grid. Going off-grid is an appealing notion and might be the preferred architecture in specialized applications. But the advantage of a connected network of distributed power producers is clear: shortfalls or downtime for one producer can be covered by a neighbor. Holding the 60 Hz frequency stable as power needs fluctuate relies (at the few-second timescale) on the inertia of the turbines pushing the electricity out and the inertia of the vast number of electrical motors spinning day and night in the houses, hospitals, buildings, and factories of industrialized societies.

Conclusion

Solar and wind have become the standard for electricity production in many jurisdictions. In a way, they are redefining the concept of base load. Base load used to be characterized by 24/7 supply as the foundation around which other supply sources were draped. This shift in definition to an intermittent supply is driven by the low delivered cost and the renewable energy feature. But the temporal variability must be addressed. We generally conclude in this chapter that short-term gaps can be filled with batteries, but multiple days of Dunkelflaute can be handled by very few low- to no-carbon sources. In our view, these are SMRs, geothermal energy, and innovative storage means. These longer duration gap fillers are not yet developed to scale and are unlikely to be for at least a decade. In the interim, fossil fuel combustion with CCUS is the only realistic option for the long periods of doldrums. This underlines the need for rapid development and deployment of CCUS and for policy that accelerates deployment of the gap fillers.

References

Cartier, K. M. S. (2022, February 3), Good news: Rocks crack under pressure from mineral CO_2 storage. *Eos*. https://doi.org/10.1029/2022EO220064

Jackson, F. (2021). *Commercial carbon capture and use takes a step forward with carbon clean*. Forbes. https://www.forbes.com/sites/feliciajackson/2021/02/14/commercial-carbon-capture-and-use-takes-a-step-forward-with-carbon-clean/?sh=2adf22276a47

Lail, M., Tanthana, J., & Coleman, J. L. (2014). Non-aqueous solvent (NAS) CO_2 capture process. *Energy Procedia*, *63*, 580–594. https://doi.org/10.1016/j.egypro.2014.11.063

Mehta, V., & Shah, U. (2022). Opinion: India's green hydrogen policy: A perspective. *India Times*. https://energy.economictimes.indiatimes.com/news/renewable/opinion-indias-green-hydrogen-policy-a-perspective/91624663

Rao, V (2021). What is happening in the energy capital? https://rtec-rtp.org/2021/02/18/what-is-happening-in-the-energy-capital/

Rhode, E. (2021, April). *Direct air capture pros and cons*. Treehugger. https://www.treehugger.com/direct-air-capture-pros-and-cons-5119399

Richter, A. (2021). *Google, Fervo Energy partner on geothermal*. ThinkGeoEnergy. https://www.thinkgeoenergy.com/google-fervo-energy-partner-on-geothermal-technology/

Schmelz, W. J., Hochman, G., & Miller, K. G. (2020). Total cost of carbon capture and storage implemented at a regional scale: Northeastern and midwestern United States. *Interface Focus*, *10*(5), 20190065. https://doi.org/10.1098/rsfs.2019.0065

Schwager, H. (2021). *World lithium supplies*. http://large.stanford.edu/courses/2021/ph240/schwager1/#:~:text=Geographically%2C%20world%20lithium%20supplies%20are%20highly%20concentrated%20in,export%20play%20a%20huge%20role%20in%20the%20economy

Shekhar, J., Saji, S., Agarwal, D., Ahmed, A., & Joseph, T. (2021, August). *Assessing and planning for variability in India's wind resource*. CEEW Report. https://www.ceew.in/sites/default/files/ceew-study-on-impact-of-climate-change-on-wind-power-generation-capacity-india.pdf

Spector, J (2020) *The 5 most promising long-duration storage technologies left standing*. Greentech Media. https://www.greentechmedia.com/articles/read/most-promising-long-duration-storage-technologies-left-standing

Statista. (2022) *Lithium-ion battery pack costs worldwide between 2011 and 2030*. https://www.statista.com/statistics/883118/global-lithium-ion-battery-pack-costs/

US Department of Energy. (2021). *2030 solar cost targets*. https://www.energy.gov/eere/solar/articles/2030-solar-cost-targets

US Energy Information Administration (EIA) (2015a, February 25). *Wind generation seasonal patterns vary across the United States*. Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id=20112

US EIA. (2015b, December 2). *EIA electricity data now include estimated small-scale solar PV capacity and generation*. Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id=23972

Economics of Small Modular Reactors

Introduction

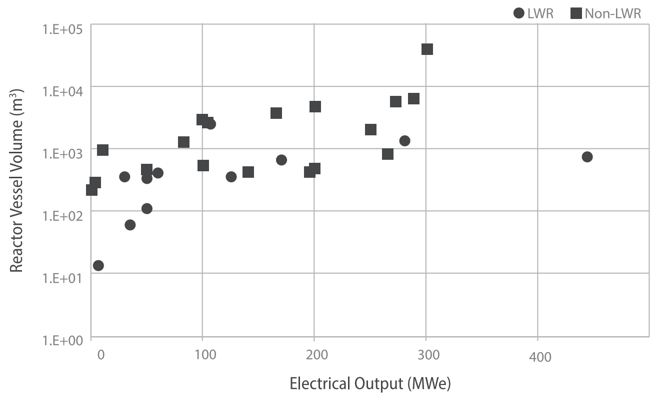
Economies of scale point to lower cost per unit produced as the size of a plant or enterprise increases. In short, sometimes bigger is better for certain industrial processes because the incremental cost of a bigger system is offset by the increased efficiency of production and by the fixed costs being shared over more units produced. Economies of scale apply for most conventional electric power plants based on fossil fuel combustion. However, they do not hold for solar power or wind power. In these cases, units (solar panels or wind turbines) need to be replicated and grouped to achieve the designed electric power production capacity. Accordingly, mass manufacturing techniques (such as assembly lines for automobile production) need to be optimized to reduce fabrication costs. Such optimization was responsible for substantial reduction in solar panel production cost that led to the rapid deployment of solar power, and to solar power now being the lowest cost power, clean or otherwise, in many parts of the world.

Following similar logic, small modular reactors (SMRs) are expected to deliver electricity at lower cost than conventional nuclear reactors because economies of scale are expected to be replaced in part by economies of mass production and by standardization of components. Analogs in other industries have demonstrated the economic benefits of both these factors.

Small Reactors: The Beginnings

The compact nuclear reactor was developed in the 1950s and used by the US Navy to power the nuclear submarine USS *Nautilus*, launched in early 1955. These early compact reactors were based on light-water moderation and cooling technology (see the box at the end of this chapter). Since the Navy selected this technology, 85% of all civilian commercial reactors worldwide have used a variant of it. This allowed decades of operational experience and learning to be applied to bringing down the cost of light water versions of SMRs. Familiarity with pressurized light-water reactors (i.e., PWRs) may also

Figure 7.1 Reactor design, size, and volume of SMRs



Source: Adapted from International Atomic Energy Agency (2020).

have been why the first design approved by the Nuclear Regulatory Commission (NRC) was for the NuScale PWR. Many other designs are being considered, though, and PWRs are by no means the focus of many countries. Figure 7.1, with more non-PWR square data points than PWR round ones (note that the LWR [light-water reactor] legend in the figure is synonymous with PWR in this book), shows this is true for all power levels being explored in SMRs.

The reactor on the *Nautilus* followed a development pattern—from test through prototype to deployment—that likely will be required for many of the proposed SMR designs. The original design, developed and tested at Oak Ridge National Laboratory (ORNL), had a 3-MW capacity—the Low Intensity Test Reactor. A higher power prototype (called S1W, which stood for Submarine Prototype1 Westinghouse) was constructed inside a section of a submarine hull and tested at the Idaho National Laboratory (Figure 7.2). Admiral Hyman Rickover famously disallowed a coffee machine to be in the hull because there would not be one in a submarine. Rickover was respected, but not uniformly liked.

Following successful testing, a 70-MWt version of S1W was installed in the *Nautilus* and operated successfully for many years. The reactor size is a best guess estimate from sources; much such information is classified. The original S1W is only now (as of 2022) being demolished and removed.

The demonstration of a successful prototype likely was a factor in the choice of PWR for commercial applications. Industry could consider

Figure 7.2 The S1W reactor in Idaho

Source: US Department of Energy (2022).

feasibility as established in the Low Intensity Test Reactor and S1W prototypes.

Part of the motivation for selecting and optimizing one design may also have been the expectation of cost reduction through learning curves common to manufacturing methods. An excellent example of this is the French nuclear industry. By standardizing key modules, France has very high penetration of nuclear in the energy mix (over 70% of electricity generated is nuclear). The delivered cost of electricity in 2019 was the lowest in Europe, at 0.17 euros per kWh. Prices were 46% and 79% higher in neighboring Spain and Germany, respectively (Selectra, 2021).

Energy Economics: Levelized Cost of Energy

The concept of levelized cost of energy (LCOE) is key to understanding the real-world economics of any energy source. It measures lifetime cost of an energy source, divided by its energy production. In the calculation, the numerator is the sum of all capital and operating costs. The denominator is the sum of all energy produced over the same period. Importantly, the approach allows comparison between disparate sources.

Levelized Cost of Energy

LCOE is calculated by first estimating the present value of the capital investment and the cumulative cost of operation over the designed lifetime. This is divided by the cumulative energy produced over the same period. It is expressed as

$$\frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where I_t is the capital invested in year t, including financing cost; M_t is the maintenance and other operating expense in year t; F_t is the cost of fuel in year t; E_t is the total electricity produced in year t; r is the discount rate; and n is the operating life of the system.

LCOE inherently includes the capacity factor, which measures the efficiency of equipment utilization. Capacity factor is an important concept, defined as the energy produced over a period divided by the nameplate capacity of the plant over the same period. The nameplate capacity is the maximum output possible from the plant.

The nameplate capacity is never achieved, because there always are periods of time when the plant is either not producing or producing suboptimally. There are many reasons for downtime, but the principal of these is the time spent in maintenance and repair. Another common reason for reduced utilization is the availability of the fuel. Notoriously low-capacity-factor generators are wind- and solar-based renewables. This is because the *fuels* of solar intensity and wind speed are variable due to diurnality and seasonal fluctuations (see Chapter 6). Solar panels also have decreased efficiency of up to 40% when particulate matter is deposited on them (Bergin et al., 2017). Solar energy has a theoretical maximum of about 25% capacity factor (Andrews, 2016), with world averages running close to 18%. Even the high solar intensity areas, such as the desert state of Rajasthan in India, are limited to this. In fact, the reported capacity factor in Rajasthan is 20%. The explanation could be dust or other pollution-related reduction in efficiency (Valerino et al., 2020) or maintenance breakdowns. The cautionary tale here is that mere high solar intensity is only a starting point for desirability of an area for solar power.

Baseload plants are defined as those intended to run as continuously as possible to meet the needs of their users. These tend to be the ones with high capital cost, such as nuclear and coal, where a reduced capacity factor extends the payback period. Conventional geothermal, which can be low capital, is also usually run continuously for operational reasons. A relatively high capital cost generator is dam-based hydroelectricity. The capacity factor of the Hoover Dam has been as low as 20%. But dams serve other purposes, such as flood control, and they can also be a medium for storage of electricity during periods of excess production. This is commonly being done in Europe, where excess wind electricity is sent to Norway and used to pump water up a dam to be released when needed. This operation is known as pumped storage. Nuclear power enjoys the highest capacity factors when run as baseload. In the United States, they are in excess of 90%, compared to coal at 70%.

At the other end of the spectrum from baseload plants are the peaking power plants, or peakers. These are designed to augment baseload in periods of high electricity demand, typically daylight hours, and especially during excessive heat or cold weather events. The LCOE for such plants is necessarily high because of being underutilized. But this expensive form is necessary in many situations. Natural gas is the preferred fuel for peakers, in part because natural gas power generation has relatively lower capital cost and because gas turbines can be spun up and down rapidly without losing efficiency.

While LCOE is an effective parameter for estimating the economics of any form of energy in each locale, many other factors determine the actual cost of production at a given time. This analysis of sensitivity to externalities is known as a tornado chart. As an example, a tornado chart for wind energy in 2010 is reproduced in Figure 7.3. Whereas the baseline LCOE is computed to be US$71 per MWh, it is based upon assumptions regarding parameters which, if different, could significantly move the cost in either direction.

Clearly, capacity factor is the largest component of cost variability. The LCOE is also sensitive to initial capital cost. While this may seem obvious, different forms of energy have variability in this regard. Conventional nuclear has been notorious for cost overruns. For example, two such new reactors being built in the state of Georgia are 5 years behind schedule since approval in 2012, and the cost has ballooned to US$28 billion, which is double the original planned figure. SMRs are expected to be less prone to overruns, for reasons

Figure 7.3 Wind LCOE sensitivity analysis

Note: AOE = annual operating expenses; ICC = initial capital cost; LCOE = levelized cost of energy.
Source: US Department of Energy (Tegen et al., 2012). Reprinted with permission from the National Renewable Energy Laboratory, https://www.nrel.gov/docs/fy12osti/52920.pdf, accessed September 16, 2022. Please note that the NREL developed figure is not to be used to imply an endorsement by NREL, the Alliance for Sustainable Energy, LLC, the operator of NREL, or the U.S. Department of Energy.

discussed later in this chapter. The sensitivity to annual operating expenses is low for wind, but could be high for natural gas, where the fuel cost tends to be volatile. At this writing, natural gas in Europe costs about four times what it did a year ago (Taylor, 2021). This is high enough off the norm to cause switching to coal and oil. In the United States, where natural gas prices doubled, albeit still to a figure six times lower than the price in Europe, coal power had a strong uptick (US EIA, 2021). Nuclear energy, although able to ramp up and down, tends to run at constant, and high, capacity factors of over 90%.

Can SMRs Compete Economically?

The most distinctive features of SMR economics are the size and modularity. However, in the absence of the usual economies of scale, small units must be designed to be more efficient. The innovation that achieves that is process intensification. The US Department of Energy Advanced Research Projects Agency-Energy (ARPA-E) has for some years run a program called Rapid Advancement in Process Intensification Deployment (RAPID) to advance this area in other process engineering applications (Palou-Rivera, n.d.). A feature of process intensification is also to make these small units capable of combination to produce larger outputs. Another feature is the objective of simplifying the components to enable mass manufacturing, thus reducing the cost of the assembled units. In so doing, economies of scale (large plants achieving economies) will have been replaced by economies of mass production.

SMR designs follow this script to a large degree. The first commercial producer of nuclear electricity was the small reactor on the *Nautilus*. Historically, therefore, small reactors preceded the large civilian ones. The Navy replicated these small reactors, so arguably the first commercial reactors were small ones. But civilian units were large, following the dogma of economies of scale, as did all chemical plants of the era. Large nuclear reactors, just the same as large natural gas-to-liquids plants (production of synthetic diesel or other liquid fuel from natural gas), are built on-site. Incidentally, the gas-to-liquids plants are also notoriously subject to cost overruns.

In contrast to conventional nuclear plants, SMRs are manufactured in factories and the subassemblies are assembled on-site. The key economic advantages are discussed below.

Low Initial Capital Costs

Because mass manufacturing methods are employed, the unit cost of subassemblies should be driven down. However, this objective is feasible only if there are large orders, and that awaits a high degree of acceptance. Complicating the issue is that currently there are over 70 different designs in various stages of development (IAEA, 2020). These comprise four classes of design, namely, PWRs, high-temperature gas-cooled reactors, metal-cooled fast reactors, and molten-salt reactors (see Chapters 3 and 4), so one would assume different factories would produce the components for each design type. With many designs, the likelihood of large orders for each offering is low. Of course, the number of offerings will get whittled down, and even today the ones deployed early are in the PWR category, including the NRC-certified NuScale and the Russian KLT-40S deployed on an offshore barge in Siberia. Gen4 has already dropped out of the race. Even if just the PWR-based SMR designs were standardized in some fashion, delivered costs would be lower.

How Deep-Water Oil Recovery Became Economical

An interesting possibility to facilitate cost reductions would be to lift a stratagem from the deep-water oil and gas playbook. When water depths exceeded the practical limit of fixed platforms, which was about a 1000 feet, well fluid handling and control (the assemblies being known as trees) had to be transferred to the seabed. These were called wet trees, as opposed to dry trees on fixed platforms. In the early going of the deep-water operations, each subsea assembly was custom designed and built. Prohibitive costs, which hampered deep water growth, and time delays led to industry joining hands to standardize all elements of the subsea architecture. The work was precompetitive and allowed for proprietary innovation, because only the interfaces had to be standard, not unlike the situation faced by electric vehicle charging. Costs and deployment timescales dropped.

Standardization through shared innovation for SMRs ought to be easier than for the deep-water oil industry because of a smaller number of actors. The Department of Energy could catalyze action in this space, especially given its avowed interest in SMRs (Granholm, 2021). Industry players might even be able to pick up learning from the RAPID program in cost reduction through standardization.

Low Maintenance Costs

Standardized mass production would focus the technically complex effort in factories rather than distributed onto greenfield sites. Spare parts could be ordered and stored in bulk and distributed to the SMR sites on demand. Quality control will be simpler because of the factory setting. Hiring and retaining production and maintenance workforce ought to be easier, in part because the factories could be located in areas with better access to qualified personnel.

High Capacity Factors

High capacity factors can be achieved because the modules will be installed in response to short-term predictions of demand, and so could be expected to be heavily utilized. In most new electricity production installations, the capacity must be figured for growth many years out. A conventional nuclear plant would be forced to have a nameplate capacity matching future growth and would run on reduced capacity factors until expected demand is realized, which has an adverse impact on LCOE. Not so with SMRs, where modules could be added in response to short-term forecasts of utilization. The ability to install individual modules on a programmed basis also improves affordability for a lot of communities. The capital investment is now spread over years, and most importantly, capability can be added only as demand picks up.

Economic Impact from Job Creation

In Chapter 8 we discuss the direct impact on the local economy of jobs created at the plant, as enumerated in the report prepared for the Regional Economic Development for East Idaho by two faculty members from Boise State University and the University of Idaho (Black & Peterson, 2019). The economic uplift includes the multiplier effect and is a direct result of the jobs during the construction and operating phases and is not very different from what one would expect from any other enterprise (see Chapter 8). The only distinctive features are the large number of jobs created compared to other energy sources of comparable output and that the average salary is higher than would be for coal-fired generators.

Cost Comparisons with Alternatives

SMRs are beginning to be compared with other low-carbon energy sources. Because very few have been built, comparisons are just estimates. This is particularly difficult because the true value of SMRs will be in the reduction in manufactured cost by economies of mass production to offset the loss of economies of scale enjoyed by the large units. Nevertheless, estimates exist in the literature, many coming from the operating companies.

In the case of NuScale, the Energy Policy Institute, a part of the Idaho National Laboratory, made a detailed estimate of the manufacturing cost (Black et al., 2017). It came close to being a bottom-up estimate based on actual manufacturing costs. The Department of Energy's Code of Accounts system was used to estimate the cost of manufacture of the SMR modules and the assembly. The fact that the NuScale reactor was modeled on a traditional PWR allowed the study to access from ORNL the costs of over 500 categories of fabrication and assembly associated with the production of a traditional PWR-12 nuclear power plant. These were provided to NuScale Power LLC, who modified them to suit their variants, which included accounting for features such as reduced components and integrated functionality, which are inherent to the NuScale design, and to a degree to other LWR-based SMR concepts as well.

For comparison, an interesting effort is that of an outfit named Energy Impact Center, which is developing an open source SMR named Open100 (Dalton, 2020) in collaboration with prominent industry actors, including the ORNL and the Idaho National Laboratory. The Energy Impact Center states that the 114-MW unit has an estimated capital cost of US$2,653 per kW, compared to US$3,850 per kW for a conventional nuclear plant 10 times that size.

These impressive estimates should be interpreted with caution, as no Open100 SMRs have been built yet. With the high rated capacity factors for nuclear, the LCOE for this plant is US$36 per MWh, compared to US$92 per MWh for the reference conventional nuclear plant. At US$36, it is highly competitive with solar. And it does not have to be (see Chapter 6).

Solar has a median capacity factor approaching 25% in the United States (Statista, 2021). This is dictated by the annual average sunlight periods, including rainy days and dark nights. Wind has similar issues, although that is more periodic by month. In either case, an attractively low LCOE is not indicative of the fact that a community cannot be served just by solar and wind. The augmentation currently is with battery storage or natural gas. If one eliminates the natural gas for low-carbon objectives, one is left with the augmentation at costs exceeding US$150 per MWh (Dyson et al., 2021). This is an excellent reason why comparisons with classic renewables cannot be just LCOE-based. A caveat: Enhanced geothermal is a true renewable and expected to come in at an LCOE under US$70 per MWh and with over 90% capacity factors.

Why US Navy Experience Did Not Provide a Learning Curve for SMR Capital Cost

SMRs are not new in principle. Small reactors were in operation in naval vessels for seven decades before the first commercial SMR version was approved by the NRC, and another decade or so before the first emplacements for utility scale power are expected to take place.

One might wonder if the US Navy experience can inform commercial SMRs. There are some 83 Navy reactors in service today that fit comfortably into the definition of SMRs from the standpoint of nameplate capacity, all being under 300 Mwe. Also, all are PWRs. The only SMR granted an NRC license to date is also an PWR. But that is where the similarities cease.

Navy reactors are primarily for motive power using steam turbine propulsion. A portion of the capacity is used for electricity generation, but that utility is subservient to the requirements of propulsion. When the vessel is docked, the reactor is switched off and shore power is used.

The net result is that the capacity factor of the fleet averages a lowly 15%.

The other big difference is that the Navy reactors use highly enriched uranium, which is defined as over 20% U-235. This is believed to be the minimum for weapons use. The Navy employs fuel with 93.5% U-235. The fuel is designed to last the lifetime of the vessel, which is usually more than 30 years. The units are built to survive combat, which translates into survival of shocks over 10 times the values designed for commercial nuclear service. Personnel are in close quarters over great lengths of time, requiring even more isolation from radiation. And on it goes, the mission is different, so the cost does not easily translate. Information for civilian use is not simply obtained even if classified information rules do not intrude, which they do.

The Navy got us our start, but we civilians are on our own now, other than hiring the odd "bubblehead" (Navy slang for submariner).

Capital cost estimates vary from the *n*th unit optimistic US$2,653 per kW from the Energy Impact Center and US$2,500 from SMR START (SMR Start, 2021), to the first unit cost given by NuScale of US$5,078. These are all *overnight* numbers, meaning as if they got built overnight, no interest payment, no overruns. Overnight numbers could be expected to be closer to the actuals for SMRs, compared to for conventional nuclear, because they are factory produced, and modularity means the timescales for full build are much shorter. Conventional nuclear has overnight numbers of US$3,850 and actuals of US$5,339.

Considering that no commercial SMRs have been constructed, one cannot be certain of the associated economics. However, at least the PWR-based versions, relying on seven decades of technology enhancement, are more than likely to emerge as economical. Certainly, they will be cost-effective supplements to the low-capacity-factor renewables, solar and wind. Just possibly, this will be the area of head start and learning-curve-based cost reduction sufficient to function as economic baseload elsewhere. The only LCOE numbers we have today are the ones claimed by NuScale. They estimate LCOE at US$64 per MWh. The first installation will be in Idaho. When the power purchase agreement is signed with those numbers, contractually binding delivery with those terms, then even those from the "Show-Me" state Missouri may be persuaded.

"Under Way on Nuclear Power"

That was the message sent by the USS *Nautilus* on January 17, 1955 (Figure 7.4). This was the first nuclear powered submarine, and it changed the face of warfare. Previous submarines operated on diesel fuel and had to be refueled often. Range of the *Nautilus* was essentially limited only by food supplies, and surfacing was not required during a voyage of any length.

The *Nautilus* used a version of a PWR, where water was the cooling agent and also the moderator for the fast neutrons. At the time, the Navy was experimenting with a sodium-cooled reactor as well. But when Captain Hyman Rickover (later he was an admiral) got the nuclear submarine sanctioned, the team leader at ORNL, Alvin Weinberg, picked the PWR in part because he thought it better suited

Figure 7.4 The launch of the ***Nautilus***

Source: Launching of USS *Nautilus* (*SSN-571*) at the Electric Boat Company, Groton, CT. January 21, 1954. Image is from the USS *Nautilus* Photo Collection, UA 475.05. Copyright Naval History and Heritage Command.

to the small size dictated by the submarine than a graphite moderator variant. It turned out to be a pivotal choice because the entire civilian nuclear industry was guided by the success of the *Nautilus*. Incidentally, the craft had other issues that limited its speed, but none were related to the nuclear power module.

One reason for the rapid advance from concept to launch was that the conventional methodology of construction of a scaled-down prototype was skipped. This decision was made by Captain Rickover, over the objections of Weinberg, and was premised on the belief that naval dominance was at stake and speed was of the essence. Conception was at ORNL, and a full-scale prototype unit was built in what is now the Idaho National Laboratory. Rickover required that a submarine to house the unit be built simultaneously in Connecticut. Since it was 82 feet longer than the conventionally powered equivalent, failure of the engine would have doomed the vessel as unpractical. Both risks, with enormous cost implications, underlined Rickover's influence, and when they proved merited, his place in history was assured. Nobody remembers the failure of the sodium-cooled reactor and the associated USS *Seawolf*, where similar corners were cut. The collective amnesia could partly be explained by the fact that the vessel was able to retrofit a PWR, and so at least the failure of the reactor did not render it a total loss.

References

Andrews, R. (2016). *Solar PV capacity factors in the US—The EIA data*. https://euanmearns.com/solar-pv-capacity-factors-in-the-us-the-eia-data/

Bergin, M. H., Ghoroi, C., Dixit, D., Schauer, J. J., & Shindell, D. T. (2017). Large reductions in solar energy production due to dust and particulate air pollution. *Environmental Science & Technology Letters*, *4*(8), 339–344. https://doi.org/10.1021/acs.estlett.7b00197

Black, G., Aydogan, F., & Koerner, C. (2017, December). *Levelized cost of electricity: Cost evaluation for NuScale Power LLC*. Energy Policy Institute.

Black, G., & Peterson, S. (2019, January 29). *Economic impact report: Construction and operation of a small modular reactor electric power generation facility at the Idaho National Laboratory Site, Butte County,* *Idaho.* Prepared for the Regional Economic Development for East Idaho (REDI) by Idaho Policy Institute, Boise State University McClure Center for Public Policy Research, University of Idaho. University of Idaho Final Copy.

Dalton, D. (2020). *Generation IV / economic modelling compares costs of SMR to conventional PWR*. https://www.nucnet.org/news/economic-modelling-compares-costs-of-smr-to-conventional-pwr-10-4-2020

Dyson, M., Shah, S., & Teplin, C. (2021). *Clean power by the hour: Assessing the costs and emissions impacts of hourly carbon-free energy procurement strategies.* RMI. http://www.rmi.org/insight/clean-power-by-the-hour

Granholm, J. (2021, November 7). *U.S. "very bullish" on new nuclear technology.* https://nukewatch.org/news-item/u-s-very-bullish-on-new-nuclear-technology-granholm-says/

International Atomic Energy Agency (IAEA)). (2020). *Advances in small modular reactor technology developments*. https://aris.iaea.org/Publications/SMR_Book_2020.pdf

Palou-Rivera, I. (n.d.). *Transforming the process industries through modular chemical process intensification*. https://www.arpa-e.energy.gov/sites/default/files/ARPA-E%20UNF%20Recycling%20Workshop%20Presentation-Palou-Rivera.pdf

Selectra. (2021). *Electricity tariffs in France: Compare electricity prices in 2021.* https://en.selectra.info/energy-france/guides/electricity/tariffs

SMR Start. (2021). The economics of small modular reactors. http://smrstart.org/wp-content/uploads/2021/03/SMR-Start-Economic-Analysis-2021-APPROVED-2021-03-22.pdf

Statista. (2021). *Capacity factors for selected energy sources in the United States in 2021*. https://www.statista.com/statistics/183680/us-average-capacity-factors-by-selected-energy-source-since-1998/

Taylor, C. (2021). Gas price surges to a record high in Europe on supply concerns. https://www.cnbc.com/2021/10/05/gas-price-surges-to-a-record-high-in-europe-on-supply-concerns-.html

Tegen, S., Hand, M., Maples, B., Lantz, E., Schwabe, P., & Smith, A. (2012). *2010 Cost of wind energy review.* National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy12osti/52920.pdf

US Department of Energy. (2022). *EM to demolish submarine reactor prototype at Idaho site*. https://www.energy.gov/em/articles/em-demolish-submarine-reactor-prototype-idaho-site

US Energy Information Administration (EIA). (2021, December 21). Annual US coal-fired electricity generation will increase for the first time since 2014. *Today in Energy*. https://www.eia.gov/todayinenergy/detail.php?id=50620

Valerino, M., Bergin, M., Ghoroi, C., Ratnaparkhi, A., & Smestad, G. P. (2020). Low-cost solar PV soiling sensor validation and size resolved soiling impacts: A comprehensive field study in Western India. *Solar Energy*, *204*, 307–315. https://doi.org/10.1016/j.solener.2020.03.118

Replacing Aging Coal Plants with Small Modular Reactors

Introduction

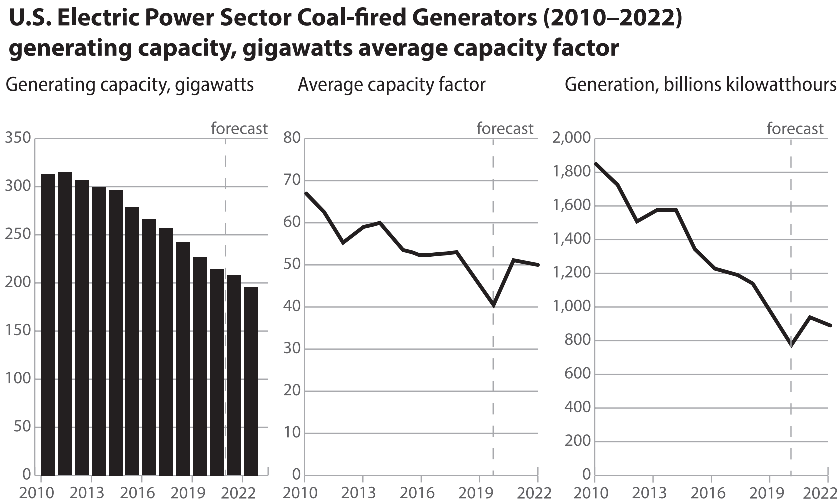
Coal-fired electricity generation has been in decline for the last decade in the United States. The reasons are competition with cheap natural gas and stricter environmental standards. As in other cases where an entire industry is in decline, governments try to stimulate new commerce in the distressed areas. The state of North Carolina went from being a tobacco, furniture, and textiles powerhouse to a biotechnology destination and, in forming the Research Triangle Park, fostering growth from scratch to become a competitor of Silicon Valley. In this chapter, we examine the viability of small modular reactors (SMRs) in reviving economies distressed by the departure of coal plants and go a step further than did North Carolina in addressing the decline of traditional industries. We examine the premise of the new enterprise serving the same function as did the departing industry and on the same footprint.

Coal-Fired Electricity Production in Decline

The US Energy Information Administration (EIA) statistics in Figure 8.1 demonstrate the decline of coal-fired generation by using three parameters. The first is generating capacity, which has declined by about 30% in 10 years. That equates to plant closures, which occurred for several reasons, including the end of the useful plant life and new, stricter limits on emissions. Reducing emissions is not economical in aging plants. The second is capacity factor, which is the efficiency of utilization of the capacity. The third is the power delivered, in kWh. The drop here is steeper than the mere fall in generating capacity.

The principal reason for the decline of coal-fired electricity has been the low price of natural gas in the United States. While natural gas is a commodity and can be expected to fluctuate in price as does oil, low prices for decades are seen as likely because the source in the United States is shale

Figure 8.1 US coal-fired electric power in steady decline



Source: Adapted from US EIA (2021).

gas. This is abundant and relatively easy to access. A potential drawback is that the natural gas infrastructure has points of leakage, and methane is 25 times more harmful than CO_2 over a 100-year time frame. But this recent recognition and active intervention still makes natural gas preferable if the leakage is kept modest (Hausfather, 2015).

For the last decade or so, the bulk of shale gas production was in the hands of small players who were highly reactive to price. Supply constraints were therefore unlikely. However, in the last few years, the COVID-19-related recession and the increasing reluctance to finance these ventures drove many of the smaller outfits into bankruptcy. The larger players who purchased those assets are no longer as reactive, and so a case could be made for firming gas prices in the future. But the decline in coal-based generation is expected to continue at a slope comparable to that experienced in the last decade, now driven more by the competition from renewables combined with an implicit price on carbon in the form of tax incentives in the United States (Europe has an explicit price via a cap-and-trade mechanism).

Increasingly, the driver for decommissioning is the growth of renewables and the forecasted increase in that growth. Today, in areas with high solar intensity, solar electricity can be delivered at a levelized cost below that possible from new coal plants (Masterson, 2021). While the intermittency of solar requires the addition of capability such as battery backup, those costs are dropping and continue to do so (see Chapter 6). More importantly, the prognosis is for improved storage mechanisms in the future.

Figure 8.1 shows the surprising fact that the capacity factor has also been dropping. This means that the percentage of time utilized is continuing to decline, as reflected in the right-hand panel, which shows the decrease in kilowatt hours (kWh) output. The reduction in power delivered is nearly 55%, much greater than the 30% reduction in the number of coal-fired plants. The public views coal plant closures as the signal for reduced coal usage, and hence lowered emissions. But this statistic demonstrates that the steep decrease in capacity factor in even the surviving plants is a strong indicator of the decline of coal. This is because, in coal-based generation, capital cost is a high fraction of overall cost, unlike for natural gas-based electricity production. Accordingly, reduced capacity factor is particularly damaging to the economics of the enterprise. If the trend in reduced capacity factors continues, coal plant retirements will accelerate.

Note the uptick in capacity factor, and hence kilowatt hours, in 2021. Although modest, it shows the responsiveness to natural gas prices, which nearly doubled in the United States in that year (IIFL Securities, 2022). Europe had it worse: Prices reached unprecedented highs, about eight times those in the previous year. The reasons for that are discussed elsewhere (Energy Explained, 2021) and not particularly relevant to our discussion except for the conclusion that the causes appear to be climate change induced.

The retirement of coal plants has hurt the communities in which they operate, from the standpoint of jobs lost and reduced state and local tax revenues. Consequently, efforts are being made to create industry that could employ laid-off power station workers. One such suggestion has been for clean energy enterprises to be built in the area around coal plant closures. In this chapter, we discuss the viability of SMR-based generation to be located precisely in the retired coal-fired plant.

SMRs in Decommissioned Coal-Fired Generators

An elegant solution to the economic deprivation resulting from the retirement of coal-fired generators is replacement with low-carbon plants that assure supply to the original customers and create jobs. Assuming that the defunct plant size was 924 MW, replacement is impractical for solar because the land mass required for an equivalent power capacity is 5000 acres (Bolinger & Bolinger, 2022), compared to the decommissioned area of about 40 acres. Furthermore, a given location may not have sufficient solar intensity, and solar requires backup. Wind energy would have similar issues, requiring even more space. The numbers for land use by wind-based generation are highly variable, but for this size output could be as high as 76,000 acres (Denholm et al., 2009).

Natural gas generation would fit in the space comfortably but would need gas supply assurance. Carbon capture could be necessary, at least at some juncture, when the cost or tax break incentives of capture and storage makes economic sense. Natural gas has already been the replacement fuel in many locations, in part because the carbon emissions are half those from coal, and in part because the efficiency of the combined cycle method is 50% greater than that of a coal plant. In the combined cycle approach, power is first produced in a gas turbine and the waste heat from there is used to produce additional electricity in a steam turbine, thus increasing the efficiency of fuel usage. In the opinion of one of us (VR), capture and storage ought to be commercially available by 2025 for less than US$40 per metric ton of CO_2 emitted. At that point, natural gas generators will, at least on the metric of low carbon levelized cost of electricity (LCOE), be highly competitive with SMRs. The principal hurdle is that gas is a fossil fuel.

An SMR emplacement by NuScale, the only US Nuclear Regulatory Commission–approved entity as of this writing, would occupy 34 acres, comfortably within the secure perimeter of the original coal-fired plant. This technology is more completely described in Chapter 3. In contextual summary, the power units are in modules of 77 MWe, which are designed to be ganged to achieve the desired power output. The decommissioned coal-fired plants could be expected to be in the range 300 to 900 MWe. The smallest of these would be served by a 4-module NuScale emplacement; the largest would need 12 modules. We will use the example of the large unit in this discussion. Note that all figures stated here are those reported by NuScale (NuScale Power, 2021) and not independently verified by the authors.

NuScale has reported on a study detailing the considerations in SMR modules occupying space previously dedicated to coal-fired generation. The footprint certainly is a good fit, with the SMR fitting within the perimeter. Some of the facilities are also usable as is, some with modifications. These include administrative buildings, cooling water systems, water supply, warehousing, transmission system connections, and fire safety provisions. The existing railhead would be of particular use during the construction phase, but less so in the operational phase, because, unlike in the case of coal, regular deliveries of fuel or other necessities are not required.

SMRs are capable of load following, so a ramp-down is feasible in the low demand periods. But equally, the power during periods of disuse could be harnessed to produce hydrogen, which, after temporary storage, could be shipped out by rail in tube trailers. That simply requires compression, although liquefaction would be an option as well, and still amenable to rail transport. But if this occurred only during the low load portions of the 24-hour cycle, the electrolyzer would be operated only for a few hours in the day, rather than continuously, leading to low capacity factors. Hydrogen with a low-carbon footprint is increasingly acquiring currency as a fuel to displace fossil fuels. Hydrogen produced in this manner during periods of low load in Europe is being inserted into natural gas pipelines up to 20% by volume, on a trial basis. In principle, any generating plant could do this. The constraint would be the fully loaded cost of the hydrogen produced and whether it is considered green (see Chapter 6).

Electrolytic Hydrogen Economics

The economics of electrolytic hydrogen are improved if the production occurs when the electricity demand is low. Each kilogram of hydrogen requires about 50 kWh of electricity to be consumed in the electrolysis. During the low demand period, the value ascribed to the electricity is low. This argument forms the basis for time-of-day pricing in some jurisdictions to incentivize use during the troughs in demand (electricity costs less after 10 p.m., so I (VR) run my clothes dryer then rather than during the day). At 2¢ per kWh, for example, the cost of electricity for generating hydrogen would be

US\$0.02 (per kWh) × 50 kWh = US\$1 per kg hydrogen produced.

A rule-of-thumb capital contribution is US\$1 per kg, assuming current projections of capital cost of US\$500 per kW (Mayyas et al., 2018) and 50% capacity factor. Add that to the operating contribution and you get US\$2 per kg, which is comparable to the production cost of *gray* hydrogen (no carbon capture) from steam methane reforming of natural gas. With a different assumption on capital cost, the figure could be commensurately higher, but active investigations are ongoing to reduce that cost (Li et al., 2020). Hydrogen supplied at US$3 per kg would be competitive, depending on the application and on the value placed on it being green.

A reduced capacity factor is a significant burden on the economics. One possibility might be to dedicate a portion of the generated power to the hydrogen production but size the electrolyzer for the power available during the periods of diminished utilization. In any event, if a scenario could be developed to produce hydrogen at the location, the rail system would be useful for dispatching the product as hydrogen or ammonia.

Economics of Replacing Coal-Fired Plants with SMRs

Economic viability is governed largely by the LCOE, but in the eyes of the local community, a key factor is what happens to the labor force. Even if the switch occurs years after the coal plant retirement, the public is likely to make the comparison. Two studies inform this question. One was conducted by University of Idaho and Boise State University faculty under contract for the Utah Associated Municipal Power Systems, which plans on installing such a facility in the state (Black & Peterson, 2019). It was an assessment of economic impact on the community without regard to whether it was sited at a decommissioned plant of any sort. The other was a report prepared by NuScale in response to queries from interested parties regarding the direct comparison of an SMR installation versus alternatives, and versus the attributes of the original coal plant (NuScale Power, 2021).

Whereas the generic coal-fired plant of the same scale (924 MWe) employs 143 persons, the substitute SMR plant is expected to employ 270, and they are higher paying jobs. The NuScale report details the principal job descriptions and compares each with comparable jobs in the coal-fired plant. They point out that most are transferable to the new job classifications, when augmented with special training. This is not entirely surprising, because both plants produce electricity, albeit with different fuels. Table 8.1 is a fragment from their report.

They make similar comparisons in other cadres, indicating that most of the personnel in the retired plant could be retained in other capacities. However, this analysis ignores the fact that, more than likely, the most

Table 8.1 Partial comparison of personnel in coal and SMR power plants

Department	Coal power plant position	NuScale equivalent position
Engineering	Thermal station engineer	Design engineer
	System engineer	System engineer
	Site project engineer	Component engineer
	Shift engineer	Staff technical advisor
	Project manager	Supply chain manager

Source: NuScale Power (2021).

suitable plant for repurposing could well have been shut down years earlier, with the employees long gone. Bolstering this point is that the first such installation is 8 years away. Nevertheless, the analysis will likely score points with the local populace by underlining the possibility of local hires. This was not the case for shale gas entry into Pennsylvania, as shown below.

New Incoming Industry Does Not Always Employ Locals

When shale gas burst upon the Pennsylvania scene in 2010, much was expected in terms of economic prosperity. While this came to pass, there were surprises in the details. The job creation was nuanced. The new jobs had features not attractive for the locals. Unlike the case of repurposing retired coal-fired generating plants, no job losses occurred in conjunction with the entrée of the new enterprises. Accordingly, the local work force could afford to be choosy.

A feature of oil and gas drilling and production is that it is performed primarily by service companies, not the oil company owning the asset. Accordingly, the employees are transients brought in for the job and later moved to other jobs wherever that may be, including abroad. While locals would have been welcome to apply for the jobs, they would have been expected to be prepared to go to another area of need even before the local drilling was completed. This nomadic way of life would not be a good fit for some.

Another feature of the jobs was that in most cases they required shifts of 12 hours on and 12 hours off. While this resulted in more full days off, the associated lifestyle was very different from the common factory practice of three 8-hour shifts. This latter is what the community would have been used to, with commensurate social lifestyle. A study in western Pennsylvania found little interest from local workers for the jobs. But the supporting jobs created were significant, representing over three jobs for every rig job eschewed by the locals (Shepstone, 2022). Prosperity resulted, but not in the manner originally envisioned.

In addition, western Pennsylvania is blessed with what is known as wet gas. This is natural gas, primarily methane, but with a high concentration of larger molecules, such as ethane, propane, and butane. Propane and butane are cryogenically separated and sold. But ethane has little use unless converted to ethylene and thence to polyethylene and other plastics. Local governments joined hands to persuade oil companies to set up conversion plants locally rather than pipelining the ethane to plants elsewhere. Having an abundance made this economical. The result was factories with jobs. Importantly, these jobs were in the conventional three-shift mode and conducive to local hiring. And they did not require travel. These were the sorts of enterprises that the locals wanted. But equally, they would not have been possible without the other type of enterprise to produce the raw material.

The Idaho study spelled out the nature of the jobs created, with many being in the community. They estimated 667 jobs in the region on an annual basis. Assuming this includes the same 270 jobs at the plant as NuScale, the rest are created in support of the plant hires. That ratio of 2.5 community jobs in support is in line with the 3.7 multiplier reported in Pennsylvania with the introduction of shale gas and associated enterprises (Shepstone, 2022). They cover a range of sectors: housing, groceries, services of all sorts at the plant and in the homes of the employees, and the like. The point is that while direct employment of displaced persons has good optics, no matter who takes the plant jobs, the other jobs often provide disproportionate economic uplift. A factor in further support is that the SMR-based jobs, being higher paying than the ones they replace, result in more discretionary spending.

The Idaho study also identifies 1600 jobs to be created during construction of the plant. While these are transitionary jobs, the 3-year period of construction is still long enough to make a material difference to the community. Overall, the study computes that the plant will increase economic output of the region by US$81 million and add US$1.97 million to local and state tax revenues annually.

Another interesting feature of the job demographics is that only 45 of the 270 workers have a 4-year degree requirement. One hundred sixty-two workers need only a 2-year associate degree or equivalent nuclear experience, and the balance can simply be high school graduates. It is telling that even a high-tech sounding enterprise largely employs 2-year degree graduates, underlining the value of community colleges. In my (VR) stint in technology leadership in the energy sector, I always encouraged my people to carefully consider the “engineer” requirement for many job classifications when an associate degree might have been sufficient. This was especially the case because we provided 9 months of domain-specific training no matter the background of the new employee.

Retired coal-fired plants can be and are repurposed with natural gas. The levelized cost is significantly lower and the emissions are much lower. The pollutants mercury and particulate matter, which are injurious to health but not greenhouse gases, are absent and lower, respectively. The benefits to short-term health are telling arguments to a local populace. Hence the rapid decline of coal-fired plants in favor of natural gas. With SMR conversion, by contrast, the levelized cost of electricity in the United States would be higher than that from natural gas, but not necessarily so if carbon capture and storage for gas is required. Certainly, in Europe and Asia, where natural gas costs are significantly higher, coal replacement with SMRs would be a useful carbon mitigation strategy.

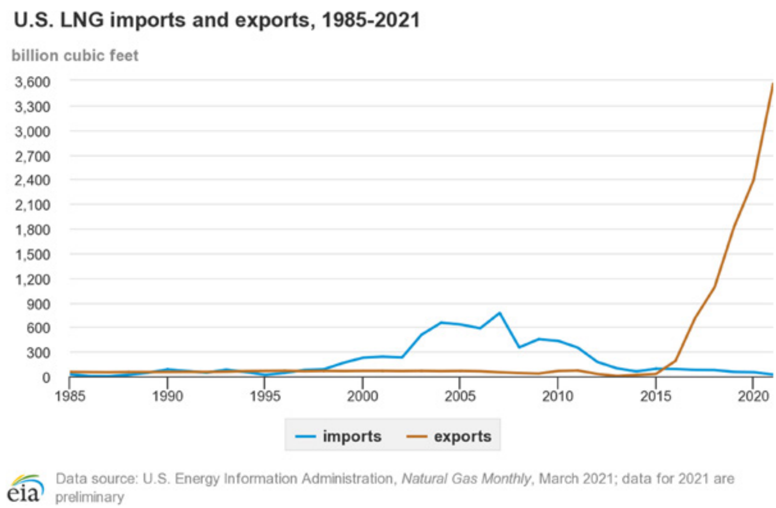
When New Plants Got Repurposed: The Story of US LNG

This is the story of repurposing newly built plants before they hit their stride for the original purpose. Repurposing is usually about facilities being retired due to old age or competition from alternatives. In the case of coal, both factors have been in play. Here is the story of liquefied natural gas (LNG) and a small energy company that took a huge gamble, lost, and then took another gamble and won. And it won by repurposing newly built plants.

Natural gas is a regional commodity. As of December 31, 2021, it cost US$4 per MMBTU in the United States, US$38 in Europe, and US$35 in Asia. This spread is at historic levels,and referring to it as unprecedented is in the same league as referring to The Beatles as successful musicians. But even in normal times the disparity is because production costs are low in the United States (and Qatar, for that matter) and pipeline transport across oceans is impractical. An undersea pipeline from Iran to India was on the cards for a while but was abandoned for political and economic reasons. The only viable approach is to liquify the gas to –161°C and transport it in insulated containers on land and in ships. The liquefaction adds about US$2.50 per MMBTU in cost and the transport adds a dollar or so depending on the distance. The fluid is kept cold by releasing small quantities and using the chilling effect of the latent heat of evaporation. At the destination, the liquid is restored to the gaseous state in what are known as regasification (re-gas) terminals.

In the early 2000s, the little-known oil and gas company Cheniere Energy decided to take a gamble on LNG becoming important for the United States. The LNG would originate from countries with plentiful low-cost natural gas, such as Qatar and Iran. At the time, the United States had seen volatile gas prices, with peaks close to US$15 per MMBTU. Renato Pereira, a vice president at Cheniere, was a neighbor of ours (VR) in Houston, and when he told me about this flyer it sounded right. That was in 2006. They got big-time investors. Then they

Figure 8.2 LNG import-to-export turnaround in the United States



Source: US EIA (2022).

got unlucky. In 2008, shale gas exploded onto the scene, and the price of domestic natural gas plummeted. Importing LNG was no longer in the cards. The Sabine Pass regasification terminal was all but complete. But no ships were going to arrive if domestic gas production took off.

This was when the Cheniere leaders took their next gamble. They decided to switch from being an LNG importer to becoming an LNG exporter, betting on US shale gas remaining cheap. That bet was right (see Figure 8.2). Turns out that repurposing a re-gas terminal to liquefaction has advantages. Some of the facilities are identical, including gas storage (this time for incoming gas, not outgoing), as well as the expensive vessel berthing and piping and associated controls. I estimate that the time to build was about half that for a greenfield site. So, they had a head start on others betting on cheap shale gas and LNG export. That start has been maintained, and they are now one of the leading producers in the world. In recent days in 2022 they must have profited handsomely from the disparity between their producer price and the price being paid in Europe. A news report suggests that the flotilla of LNG ships headed to Europe could dampen Russian saber rattling on pipeline supply (Russia accounts for 40% of Europe's gas needs).

While this certainly is a story of a little player who astutely played the hand dealt, it is also the story of an unusual situation, the repurposing of a facility very shortly after it produced the original product.

References

Black, G., & Peterson, S. (2019, January 29). *Economic impact report: Construction and operation of a small modular reactor electric power generation facility at the Idaho National Laboratory Site, Butte County, Idaho.* Prepared for the Regional Economic Development for East Idaho (REDI) by Idaho Policy Institute, Boise State University McClure Center for Public Policy Research, University of Idaho. University of Idaho. Final copy.

Bolinger, M., & Bolinger, G. (2022). Land requirements for utility-scale PV: An empirical update on power and energy density. *IEEE Journal of Photovoltaics, 12*(2). Advance online publication. https://doi.org/10.1109/JPHOTOV.2021.3136805

Denholm, P., Hand, M., Jackson, M., & Ong, S. (2009). *Land-use requirements of modern wind power plants in the United States* (Technical Report NREL/TP-6A2-45834 August). https://www.nrel.gov/docs/fy09osti/45834.pdf

Energy Explained. (2021, October 9). *The natural gas pricing crisis* [Video]. YouTube. https://www.youtube.com/watch?v=dk17ab-d93A

Hausfather, Z. (2015). Bounding the climate viability of natural gas as a bridge fuel to displace coal. *Energy Policy*, *86*, 286–294. https://doi.org/10.1016/j.enpol.2015.07.012

IIFL Securities. (2022). *Commodities buzz: US annual average natural gas prices double on year in 2021*. https://www.indiainfoline.com/article/capital-market-commodity-futures-end-session-commentary/commodities-buzz-us-annual-average-natural-gas-prices-double-on-year-in-2021-122010800313_1.html

Li, G., Chen, Z., Li, Y., Zhang, D., Yang, W., Liu, Y., & Cao, L. (2020). Engineering substrate interaction to improve hydrogen evolution catalysis of monolayer MoS_2 films beyond Pt. *ACS Nano*, *14*(2), 1707–1714. https://doi.org/10.1021/acsnano.9b07324

Masterson, V. (2021). *Renewables were the world's cheapest source of energy in 2020, new report shows.* World Economic Forum. https://www.weforum.org/agenda/2021/07/renewables-cheapest-energy-source/

Mayyas, A., Ruth, M., Pivovar, B., Bende, G., & Wipke, K. (2018). *Manufacturing cost analysis for proton exchange membrane water electrolyzers* (NREL/TP-6A20-72740). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/72740.pdf

NuScale Power. (2021). *NuScale SMR technology: An ideal solution for repurposing US coal plant infrastructure and revitalizing communities.* https://www.nuscalepower.com/technology/technical-publications

Shepstone, T. (2022). *Pennsylvania oil and gas yields nearly 500,000 jobs!* https://www.shaledirectories.com/blog-1/pennsylvania-oil-and-gas-yields-nearly-500000-jobs/

US Energy Information Administration (EIA). (2021). Annual US coal-fired electricity generation will increase for the first time since 2014. *Today in Energy.* https://www.eia.gov/todayinenergy/detail.php?id=50620

US EIA. (2022). *Natural gas explained: Liquified natural gas.* https://www.eia.gov/energyexplained/natural-gas/liquefied-natural-gas.php

The Way Forward

Introduction

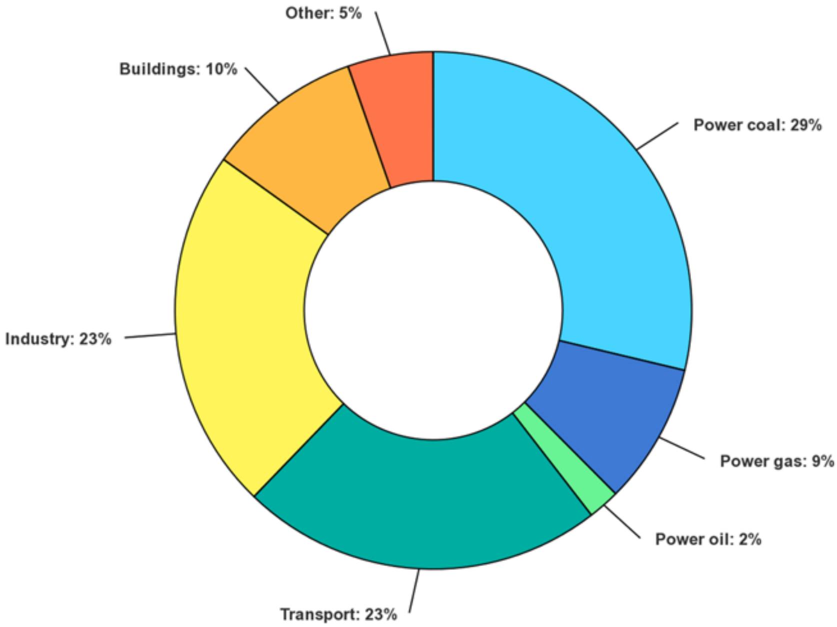
Few now dispute that climate change is an existential threat and that it is caused by the ever-increasing concentration of CO_2 (and to a degree methane) in the atmosphere. Such disputes as there are lie in how much carbon mitigation needs to be done and how soon. Vested interests also conspire to influence those debates. Effective new technology is only a first, albeit essential, step toward mitigation. It must also be economic and acceptable to society. This last is a hurdle especially for nuclear solutions; even though small modular reactors (SMRs) inherently overcome some of the concerns, perceptions are enduring and need active intervention. Geothermal approaches that include hydraulic fracturing carry some baggage as well. These externalities must be overcome for broadscale acceptance.

Figure 9.1 shows a recent International Energy Agency estimate of the energy-related sources of carbon. Estimates vary depending upon the analytical methods used, but they all agree on the biggest contributing factors: electricity generation, transportation, and industrial operations.

Electricity production, at 40%, is the largest sector and the focus of this book. But success in decarbonizing some of the other sectors has bearing on the electricity production method. An obvious example is electric vehicles, where the shift away from fossil fuel is positive for decarbonization, but the carbon footprint of the electricity source is now a factor.

The primary means for fossil fuel retirement in the transportation sector has been electrification of the fleet. To the extent that any of the electricity comes from carbon-emitting sources, part of the justification is vitiated. But only a part. The principal driver for switching to electric drive is improved energy efficiency. An electric car consumes about a third of the energy, well to wheel, of a similar-sized gasoline-powered family sedan (Rao, 2016, p. 118). That statistic alone results in carbon mitigation per kilometer traversed, regardless of the greenness of the electricity. Having said that, consumers seek green electricity for this application. Accordingly, greening of the grid is wanted, and the means to accomplish that is the focus of this book, albeit

Figure 9.1 Global energy-related CO_2 emissions by sector in 2021



Source: IEA (2021).

with a singular emphasis on one of the three prime means to augment wind and solar, namely, SMRs.

Electrification of transportation is also being achieved with hydrogen fuel cells as the source of electrons, rather than batteries. The latter is in the lead and may remain so because of the power of incumbency in a capital-intensive industry, such as automotive production. But hydrogen is more likely to be the fuel for heavy transport vehicles and possibly aircraft. One source is going to be electrolytic hydrogen using green electricity during periods of low load. This source is also likely to be used industrially and in buildings as a partial or full replacement for natural gas. In recognition of this, the Indian government has announced several policy initiatives (Mehta & Shah, 2022).

Also, iron and steel producers are seeking routes to green steel. Three principal directions are being investigated. One is electrolytic reduction of iron ore (Koutsoupa et al., 2021); and to be green, the electricity required must be carbon free. The second is direct reduction of iron, modified to use hydrogen as the reducing agent in place of synthesis gas (International Iron Metallics Association 2022). Again, the hydrogen would need to be green, and green hydrogen is expected to be a part of the carbon-free electricity scheme, as discussed in Chapter 6. The third, carbon capture and storage during conventional iron blast furnace production, has no direct bearing on the production of electricity.

Policy Enablers for Green Electricity

This brings us to one of the foci of the chapter: policy enablers. Scaling of new technology benefits immensely from governmental action. Many agree that a primary reason for the low cost of solar panels today is central government policies, such as those of Germany, where elements such as feed-in tariffs and direct subsidies for panels allowed investment in research and manufacturing methods (Kavlak et al., 2018). The implied guarantee of demand allowed manufacturers, especially in China, to invest in mass production methods, which inevitably drove down cost. India had a similar experience with LED lighting, where they went a step further than Germany. A government agency made bulk purchases through competitive bidding and redistributed the savings to citizens with subsidies. The high-volume purchase program was in part responsible for a dramatic drop in cost. The cost of a 7-W LED bulb (roughly the equivalent of 55-W incandescent) dropped from INR 310 to INR 73 (US$1) within a year (Singh, 2015). Similar innovative policy measures ought to be investigated to subsidize the part of the value chain most effective in accelerating the adoption of a desired carbon mitigation means. One such mechanism is described in the following box.

The *Aadhaar* Card

In a somewhat allied space, India launched the *Aadhaar* card, basically the equivalent of a US Social Security card on steroids. Every citizen has one, and associated with it is a free bank account. This transformed the ability to provide subsidies to low-income people by cash deliveries to their accounts, thus avoiding the inefficiencies in distribution when the subsidies were directly on commodities such as kerosene for cooking. With past policies on subsidies, due to the inefficiencies, including diversion, only a fraction of the benefit reached the beneficiaries (Jain & Ramji, 2016). The card implementation also moved much of the transactional economy out of cash to electronic payment. Aside from being a stimulus for growth, in part by making borrowing faster and simpler by minimizing verification of financial status, this measure also reduced tax avoidance, resulting in more tax revenue for subsidies. Rare is the policy measure with such broad positive impact on the populace. Rarer yet is one that slashes red tape in the process.

Solar and Wind

Solar, wind, and the three key temporal gap fillers have different needs for incentives to drive scale. Wind on land is often most abundant in mountain valleys. The land requirement is also large, three orders of magnitude more than needed for geothermal or SMRs. The policy support for wind comes in the form of aiding investment in grid connection and possibly in government land access for both the wind farms and the grid. Existing laws may need to be reversed or amended. An example is the so-called Ridge Law in North Carolina, which does not permit tall structures at geographic elevations over 3,000 feet. An amendment explicitly permitting wind farms and associated generators may be needed. Ambiguity breeds challenges, which equal delays.

In some instances, traverse through sensitive areas could be a factor (see the first box in Chapter 1, "The Grid Needs Fixing Too"). Any grid through wooded areas is fraught with difficulties. Climate change-associated incidents of wildfires are known to be caused in part by downed power lines (Rao & Vizuete, 2021, p. 157; Penn & Eavis, 2020). For this and other resilience arguments, we expect that policies may limit long power lines, especially through woodland, which would curtail land-based wind assets.

Offshore wind installations have their own hurdles in public perception, which translate into local policy. Many coastal communities do not permit them within sight, which could push the structures into deeper waters, increasing the cost of the units and transmission lines. Environmental impact studies are frequently challenged and could delay projects.

Solar faces fewer policy hurdles than wind. Here, too, large tracts may need grid expansion to supply communities such as major cities. But solar has more distributed architecture, including rooftop units. The policy enablers here are largely in the province of fit with the monopoly granted to utilities in the United States. Net metering, which essentially allows the electricity meter in a home to spin backwards when utilizing the local solar unit, is a step forward. Germany's feed-in tariffs have been in place for decades and are credited with being a factor in the plummet of the cost of solar panels.

The Gap Fillers

The diurnality and seasonality of solar and wind electricity production causes gaps in output that need filling for grids to enjoy 24/7 capability. Some, such as pumped hydro, exist and are valuable where available (Chapter 6). In our opinion, a concerted effort is needed in three areas to achieve the carbon-neutral scale required to keep up with the rapid expansion of solar and wind: SMRs, geothermal energy, and innovative storage means. Business as usual in the policy realm will delay the adoption rate. The longer that takes, the longer will be the reliance on fossil fuel as the gap filler. While the relatively benign natural gas is the major player here, speed is still of the essence.

Geothermal and SMRs face similar policy hurdles in the form of permits to operate. Geothermal has it a bit easier because of the similarity to conventional oil drilling. One version of geothermal, the enhanced geothermal system, faces issues with induced seismicity during fracturing operations. But these too are similar to those faced by shale drilling, wastewater disposal, and geologic storage of CO_2. Policy responses have been variable in these spaces. In the UK, shale drilling has been banned based on this issue. In the United States, state energy commissions have taken individual steps, including the requirement of monitoring stations. For geothermal systems, similar steps could be taken by the US Department of Energy to codify acceptable monitoring and control means to minimize the risk. The requirement for active seismic monitoring, at least for early wells, could be a relatively low-cost way to allay concerns.

SMRs face a steeper regulatory climb, in part due to the absence of operational history in all but water-cooled reactors. The NuScale design mentioned in Chapter 3 was recently approved by the Nuclear Regulatory Commission. This was a 5-year process though, and first emplacements are still not expected till 2028. In contrast, the first commercial geothermal installation (a 5-MWe system by Fervo Energy for a Google data center in Nevada) could come as soon as 2023 (Richter, 2021a).

Government stimuli for SMRs in any country could follow the familiar instruments of loan guarantees, long-term purchase agreements, and policy changes, such as defining electricity from SMRs as clean energy. In 2022, the EU declared investments in nuclear as sustainable (BBC News, 2022). Such measures would encourage further innovation and speed implementation.

Governments could also lead the way on adoption by installing SMRs at public facilities. Defense departments could fast track the use of SMRs for assuring resiliency at military bases. Familiarity with transport of nuclear materials would make even the infrequent fuel replacements safer than in civilian operations, and eventually provide a template for civilian facilities. The US Ellington Field Joint Reserve Base has already contracted to pilot an advanced geothermal concept (Richter, 2021b). Other military installations could follow suit with SMRs; their time horizon is longer, but the action would certainly send a policy signal. The US Department of Defense gas-cooled SMR Project Pele, mentioned in Chapter 3, is a small, but welcome, first step in this direction.

Hydrogen

Green hydrogen is becoming increasingly important as a storage solution. It takes its place with green ammonia and methanol as a viable fluid storage means. It got its start with periods of excess electricity needing a use because long-term storage was too costly. As discussed in Chapter 6, load-following gap fillers will have periods of overcapacity, and electrolytic hydrogen is a solution. Policy has been considered in Europe to allow up to 20% hydrogen to be mixed in natural gas pipelines (Kanellopoulos et al., 2022). At those levels, all downstream users are able to adjust their equipment to handle the mix, and the measure gives a clear signal to support this use of electricity during low utilization of any part of the renewable energy mix.

Similarly, India is doubling down on hydrogen. Solar- and wind-based production have exceeded targets and hydrogen is seen as part of the mix. The government took the unusual policy step of designating hydrogen from biogas reforming as green (see Chapter 6). As a reminder, this is the methane from biomass sources that is processed to produce hydrogen. When the policy was released, one newspaper op-ed suggested that further policy could facilitate blending of the hydrogen with other methane sources, including biogas, for use in cities (Bhatiani & Rao, 2021). This would facilitate faster adoption of methane–hydrogen mixes. The need for such a policy is in part to accommodate the fact that biogas can contain small amounts of CO_2, which ordinarily would not meet conventional pipeline specifications, and yet could be tolerated by burners in domestic use.

Advantages of Modularity

A singular distinguishing feature of both SMRs and geothermal plants is that they are modular, with the ability to aggregate to attain almost any size from 10 to 1000 MWe. Modularity improves the economics because the modules can be added as demanded by the expected load. This is similar to just-in-time methods for optimizing manufacturing economics by minimizing inventory carrying costs. It is particularly important in the nuclear sector because the high capital cost of conventional large-scale reactors exacts a severe penalty for low-capacity factors caused by the plant being designed for future growth.

The modular feature also allows the plants to be distributed in communities, without reliance on a national grid. Grids are notoriously prone to damage by natural disasters such as hurricanes, with such disasters expected to increase in frequency due to climate change. Distributed power can be more resilient. Critical capability such as at military bases would benefit from a captive power producer. Modularity can make it fit any size of base. Data centers are equally critical for businesses to operate. Owners are already taking steps to have dedicated production, and in the case of the big three—Google, Microsoft, and Amazon—all aspire to accomplish this with carbon-free electricity (see Chapter 5). Grid supply may continue to exist, but the bulk of the load would be from the captive producer. The same could apply to far-flung communities. Distributed power also provides protection against sabotage.

Externalities Affecting Clean Energy Economics and Mix

The principal externality faced by solar and wind energy production is the variability in intensity and duration of the "fuel." This book has focused on measures to handle this intermittency with gap fillers. However, each gap filler faces unique externalities. Nuclear energy faces hurdles in societal acceptance, as discussed in Chapter 5. Advanced geothermal systems involve drilling, and in the case of variants most further along, hydraulic fracturing as well. Hydraulic fracturing must deal with the public perception of earthquakes potentially caused by the activity. While these can, and are, addressed by practitioners, local and national governments can take stances.

Much as nuclear energy production is essentially banned in Germany, so is hydraulic fracturing in France and Switzerland. These are examples of government policy intruding on the clean energy mix. Ironically, these countries import energy from countries that utilize the banned technologies. Germany routinely receives nuclear-sourced electricity from France. In March 2022, France was the largest destination for liquified natural gas from the United States (Weber et al., 2022), and most of the US natural gas production uses hydraulic fracturing.

The Russian invasion of Ukraine in 2022 introduced an externality that had been only hinted at in the past: the use of energy as a weapon of political will. Russia had punished Ukraine in January 2009 with a cessation of natural gas supply for southern Europe. Despite a show of strength, Europe, especially Germany, shifted to greater reliance on Russian natural gas. Now that decision is severely in question. Even Germany ought to rethink its Fukushima-driven decision on nuclear energy. The intrinsic safety of SMRs could provide cover for a policy revision.

The more generic point is that the Russian invasion of Ukraine has changed the equation on the clean energy mix. Today natural gas is a key to filling solar and wind production gaps, and the Russian invasion has, at least in part, caused prices in Europe to quadruple at times. China is the largest supplier of solar panels and associated parts. No longer unthinkable is the possibility that solar panel availability will be impaired for political reasons. Costs could rise and solar could lose its positioning as a low-cost producer. SMRs may not be greatly impacted, except the variants that use highly enriched uranium (much of which comes from Russia). Geothermal may be the least affected by politically motivated externalities. Given these inferences, governments could do well to accelerate the deployment of both SMRs and advanced geothermal systems.

A Last Word

A society's actions reflect the consensus views of its population. We elect our civic and political leaders, and their decisions reflect what they believe the citizens want. This is not always obvious in contentious political times. But it is the only way forward in a modern society.

This book has been an effort to inform that debate on climate and energy. And if you have read this far, you are aware that there are not always easy choices and answers. The debate often appears to be two (or more) sides talking past each other. But there are real issues to be confronted. With a sense of urgency.

If there is one thought we want to leave you with, it is this. Solar and wind have become the low-cost, low-carbon base for many utilities. But they have an intrinsic shortcoming: diurnal and seasonal variations causing gaps in output. These gaps are best filled by some combination of low-carbon constant output technologies, such as SMRs and geothermal energy, which are close to being available at scale now, and by innovative storage solutions that are in development. Governments can and must take policy measures to accelerate the scale of adoption of these carbon-free solutions. Every year delayed is a year in which new fossil fuel-based capacity is added to fill the gaps of an ever-increasing solar and wind base. A half step back for every step forward is not how to reach a carbon-free future. Policy measures to accelerate the adoption of gap fillers will be essential for speedy realization of a fully carbon-free electricity supply. Finally, SMRs and advanced geothermal systems are the carbon-free power generation systems most resilient to the deployment of energy as a weapon of political will. They should be given priority.

References

BBC News (2022, February 2). *Climate change: EU moves to label nuclear and gas as sustainable despite internal row*. https://www.bbc.com/news/world-europe-60229199

Bhatiani, G., & Rao, V. (2021, June 30). Boosting the gas economy. *The Hindu BusinessLine*. https://www.thehindubusinessline.com/opinion/boosting-the-gas-economy/article35041571.ece

International Iron Metallics Association. (2022). *DRI production*. https://www.metallics.org/dri-production.html

International Energy Agency (IEA). (2021). *Global energy-related CO2 emissions by sector*. https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-by-sector

Jain, A., & Ramji, A. (2016). Reforming kerosene subsidies in India: Towards better alternatives. https://www.iisd.org/system/files/publications/reforming-kerosene-subsidies-india.pdf

Kanellopoulos, K., Busch, S., De Felice, M., Giaccaria, S., & Costescu, A. (2022). *Blending hydrogen from electrolysis into the European gas grid* (JRC126763; EUR 30951 EN). Publications Office of the European Union. https://doi.org/10.2760/908387

Kavlak, G., McNerney, J., & Trancik, J. E. (2018). Evaluating the causes of cost reduction in photovoltaic modules. *Energy Policy*, *123*, 700–710. https://doi.org/10.1016/j.enpol.2018.08.015

Koutsoupa, S., Koutalidi, S., & Bourbos, E. (2021). Electrolytic iron production from alkaline bauxite residue slurries at low temperatures. *Johnson Matthey Technology Review*, *65*(3), 366-374. https://doi.org/10.1595/205651320X15918757312944

Mehta, V., & Shah, U. (2022). Opin'on: India's green hydrogen policy: A perspective. *India Times*. https://energy.economictimes.indiatimes.com/news/renewable/opinion-indias-green-hydrogen-policy-a-perspective/91624663

Penn, I., & Eavis, P. (2020, June 18). PG&E pleads guilty to 84 counts of manslaughter in camp fire case. *New York Times*. https://www.nytimes.com/2020/06/16/business/energy-environment/pge-camp-fire-california-wildfires.html retrieved June 20, 2020

Rao, V., & Vizuete, W. (2021). *Particulates matter* (Emerging Issues in Analytical Chemistry Series). Elsevier and RTI Press.

Rao, V. (2016). *Shale oil and gas: The promise and the peril* (2nd ed.). RTI Press.

Richter, A. (2021a). *Google, Fervo Energy partner on geothermal*. ThinkGeoEnergy. https://www.thinkgeoenergy.com/google-fervo-energy-partner-on-geothermal-technology/

Richter, A. (2021b). Sage Geo to explore geothermal closed-loop for U.S. Air Force base. https://www.thinkgeoenergy.com/sage-geosystems-to-explore-geothermal-closed-loop-for-u-s-air-force-base/

Singh, S. (2015) LED lamp production up 30 times to 3 crore a month. *India Times*. https://economictimes.indiatimes.com/industry/energy/power/led-lamp-production-up-30-times-to-3-crore-a-month/articleshow/49795328.cms?from=mdr

Weber, H., Wyeno, R., & Mouratis, A. (2022, April 4). France top destination for US LNG in March amid Europe supply disruption fears. *S&P Global Commodity Insights*. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/lng/040422-france-top-destination-for-us-lng-in-march-amid-europe-supply-disruption-fears

About the Authors

Chris Gould is an Alumni Distinguished Undergraduate Professor of Physics Emeritus at North Carolina State University. He served for a decade as Head of the Department of Physics. He later served for seven years as associate dean in the College of Physical and Mathematical Sciences, and a year as interim head of Biological Sciences. He is a nuclear physicist by training, with interests in cosmology, energy research, and science education. He has a PhD from the University of Pennsylvania and a BSc from Imperial College, London. He has held visiting appointments at Los Alamos National Laboratory; the Institut fur Kernphysik, Frankfurt; the Atomic Energy Institute, Beijing; the University of Petroleum and Minerals, Dhahran; and the Oak Ridge Center for Advanced Studies. He is a Fellow of the American Physical Society. As a member of the KamLAND collaboration, he was co-recipient of the 2016 Breakthrough Prize in Fundamental Physics "*For the fundamental discovery and exploration of neutrino oscillations*."

Vikram Rao is the executive director of the Research Triangle Energy Consortium, a nonprofit in energy founded by Duke University, North Carolina State University, RTI International, and the University of North Carolina at Chapel Hill.

He advises Alchemy Sciences, BioLargo Inc., Clyra Medical Technologies, Cybele Microbiome, Fervo Energy, Obantarla Corp., RTI International, and Sage Geosystems. He retired as senior vice president and chief technology officer of Halliburton Company in 2008 and followed his wife to Chapel Hill, North Carolina, where she was on the faculty of the University of North Carolina. Later that year he took his current position. He is a past chairman of the North Carolina Mining and Energy Commission.

He received his BTech in Metallurgy at the Indian Institute of Technology, Madras, India, followed by an MS and PhD in Materials Science and Engineering at Stanford University. His love of writing commenced as an undergraduate, when he helped found the campus monthly *Campastimes* and was recognized at commencement for his column *Caricatures*. His first book with RTI Press, *Shale Gas: The Promise and the Peril*, was used in nine courses and is available on open access. This will be his third title with RTI Press. In the intervening years were two books with Elsevier. Three books, including this one, were co-authored. His fun book of vignettes with Notion Press, *A Stranger in No Land: Tales of Assimilation*, was released in May 2022.

He has been married for 48 years to Susan Henning, currently Emerita Professor of Medicine at the University of North Carolina at Chapel Hill. Their border collie, Abbie, stands ready to herd any intruder safely into the home.

There is a new world order in electrical energy production. Solar and wind power are established as the low-cost leaders. However, these energy sources are highly variable and require constant electrical power. Alternative sources must fill the gaps, but only a few are both economical and carbon-free or -neutral.

This book presents one such alternative: small modular nuclear reactors (SMRs). The authors describe the technology, including its safety and economic aspects, and assess its fit with other carbon-free energy sources, storage solutions, and industrial opportunities. They also explain the challenges with SMRs, including public acceptance.

The book aims to help readers consider this relatively new technology as part of an appropriate energy mix for the future and, ultimately, to make their own judgment on the merits of SMRs.

Vikram Rao is Executive Director of the Research Triangle Energy Consortium (RTEC), a nonprofit in energy. **Chris Gould** is an Alumni Distinguished Undergraduate Professor of Physics Emeritus at North Carolina State University.

The series *Energy Options in a Carbon-Constrained World* provides concise, science-based books to inform debates on climate and energy. Each volume presents a cross-disciplinary discussion of a specific technology in the context of carbon mitigation options and strategies developed to combat, stabilize, or reduce effects of global warming. The series editor is **David C. Dayton**, Senior Fellow and Director, Biofuels at RTI International.

RTI INTERNATIONAL

RTI Press Publication No.
BK-0026-2301