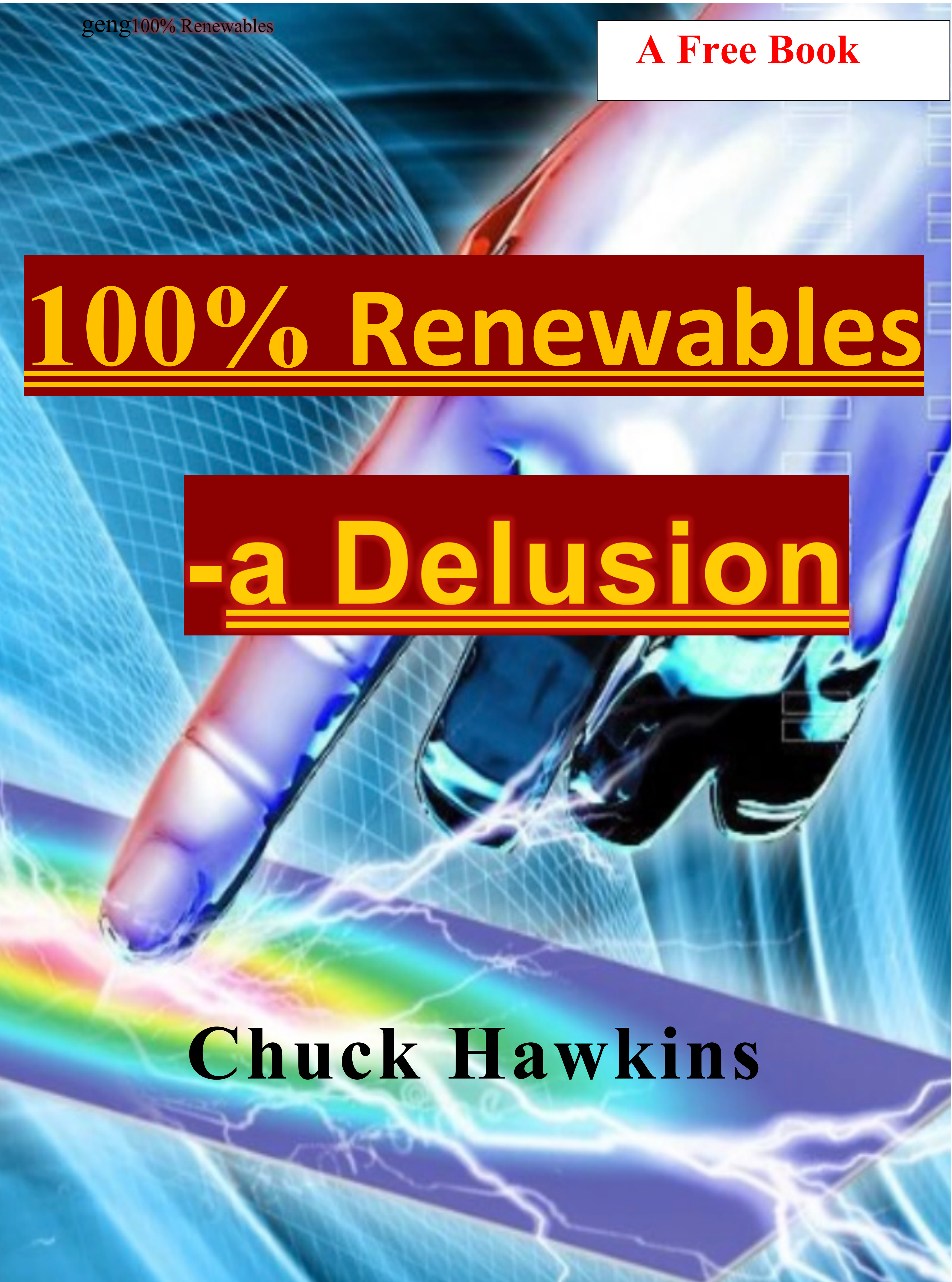

geng100% Renewables

A Free Book

100% Renewables

-a Delusion

Chuck Hawkins

100% Renewables
- a Delusion

By

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Part I

Complexities of Our Baseloads

Part II

Advanced Nuclear Reactors

March 22, 2022

Preface

A Delusion Is a Fixed Belief That Is Not Amenable to Change in View of Conflicting Evidence.

Merriam-Webster

There is increasing public chatter about forcing public utilities and cities to commit to use 100% renewable energy to clean our air and slow climate change by a certain date. There are several renewable energy sources, but it has become common for some politian's running for office to proclaim their support for 100% solar and wind. This implies that coal, natural gas, and even nuclear be eliminated in the false belief in a 100% renewable energy takes over.

Data show that this 100% goal is not even closely possible now nor in the near future for the majority of energy sites around the world. This book presents data and explains why, and what are the options. Removing the fossil fuels coal, gas, and oil is a worthy and urgent goal, but renewables are not the answer. Compelling data show that renewables have several limitations including an inability to supply 24/7 consistent and full dependable power to large populations. Battery storage to supplement renewables in not a cure to allow renewables to guarantee reliable 100% power delivery for days or months.

Coal, natural gas, nuclear, and oil are the current baseload energies that we use to deliver 24/7 constant power to large populations. Solar, wind generators, hydroelectric, geothermal, and other renewables deliver power, but they are mostly not predictable, are restricted to specific locations, and cannot operate 100% of the time. There are special cases where communities can deliver near 100% power supplied by renewables. But their geographic uniqueness is not transferable, nor is there an abundance of such communities.

Which energy source is "best"? When you dig into the details, best disappears, and you see interactions and limitations. But we can distinguish energy sources that kill fewer people, produce limited or no emission of poisonous toxins or greenhouse gas emissions, occupy smaller construction footprints as opposed to others that require large fractions of land to deliver limited power. The data eliminate all but nuclear reactors, and especially the advanced thorium nuclear designs that clean up the deficiencies of our present uranium nuclear reactors. We will present data that address the myth that nuclear reactors kill people and are not safe.

There.is a deep issue beneath our comparative examination of energy sources. A population growth of 2-billion more people on earth by 2050 and a US increase of about 125 million forces the decision as how do we do it. How will me increase our power generation? And extreme hot weather drives an increase in air condition power to cool off regions like the American southwest. How do we protect our utility equipment in massive flooding and high winds? Certain energy sources are easier to protect, but someone else should write that book.

Nuclear reactor data show it to be the safest, cleanest air, most reliable, and the most efficient method of generating electricity for all level of populations. Despite this, the current nuclear designs called light water reactors and boiling water reactors have deficiencies. These deficiencies are worked out with advanced designs especially the thorium reactor. The nuclear reactor deficiencies are addressed in later chapters.

This book is offered as a free download. I have been through the standard book publishing routine four times. Although there are good editors who encourage and smooth the way, I have chosen a well-worn route practiced by me and millions of others. And that is that most of our publications are offered free. I chose good Internet photographs to allow color visualization of this broad, complex topic. I hope and believe that the publication Fair Use Laws will protect these downloads.

This information is intended to achieve a better understanding of serious energy choices now before us. We can no longer tolerate politicians who proudly proclaim their scientific ignorance and impede solutions.

I know about this; I live in Florida.

PART I

Limitations of Solar, wind, and Hydroelectric Renewables Fuels

Chapter 1
Introduction

My grandfather rode a camel, my father rode a camel, I drive a Mercedes, my son drives a Land Rover, his son will drive a Land Rover, but his son will ride a camel.

Sheikh Rashid bin Saeed Al Maktoum
(Former Prime Minister, United Arab Emirates)

One of our earliest memories often comes from smell. I spent childhood years in a small Illinois farm village where the air was often heavy with the smell of smoke from burning coal. The Illinois Central Railroad tracks ran through the village, and the large freight trains heading south from Chicago were often pulled by up to three large coal burning steam engines. Those enormous moving machines rattled the kitchen cabinet dishes. And passengers rode south on the musically famous "Train They Call the City of New Orleans." That sweet smell of coal in the air on a cold day also meant houses warmed from basement coal furnaces and kitchen coal stoves. That sweet smell is still with us.

We walked to school each morning and walked home for lunch. But none of us knew then or cared that the smoke from coal contained more than 80 noxious chemicals such as arsenic, lead, mercury, uranium, and particles. Our childhood interest in trains was in the shape of crushed pennies that we put on the track and not on what we put in our lungs. It was a different world.

What does electricity generation have to do with railroads in a small Illinois farm town long ago? Plenty - It matters how we generate electricity and coal is a lethal source of electrical energy. This book evaluates the energy sources that we select to bring constant and reliable power to our lives. The renewable forms of energy sources such as wind, solar, biomass, hydroelectric, geothermal, and tidal and others do reduce the dangerous and deadly toxic fossil fuel emissions, but they produce power on their own terms and that is only when the sun shines or the wind blows, or the hydroelectric dam water reservoir is full. Renewables can be useful, but are typically weak at powering large populations, are location specific, and we cannot predict their power output. Except for tidal and geothermal, renewables depend on the weather.

Public consciousness is growing in renewable energy as a solution to fossil fuel toxic emissions that affect degrade our air quality and climate change. Renewables are a fossil free fuel, whose definition is a power generated from the natural surroundings such as the sun that powers solar photovoltaics, wind, hydroelectric, and biomass. Ocean tides and geothermal are non-solar renewables taking most of their energy from the gravity of the moon and high radioactive driven temperatures deep in the Earth. Biomass is often listed as a renewable but burning timber despite claims of renewable purity is a CO_2 and sometime toxin emitter. Data will show that except for hydroelectric power under special conditions, renewables cannot provide 100% of our power or even come close.

Energy sources are defined by the fuel they consume - such as the coal, natural gas, and nuclear reactors that are called *baseloads*. Baseload energies use large power plants centrally located to transmit and distribute constant power to distant customers. The baseload power output is large in the billions of watts (GW). The core property is that baseloads deliver dependable, constant power throughout a 24-hour day. Renewables cannot do that so their unpredictable power contribution must be backed up by a baseload, and that is one reason why we are anchored to a baseload source. A solar farm with a peak power of 50 MW must have a near 50 MW baseload reserve with the local power utility to cover customers when the sum isn't shinning. That backup reserve comes from either coal, gas, oil or nuclear energy. This book will detail the pros and cons of the baseloads and renewables and arrive at a best energy path conclusion.

Seven baseload power generating technologies are evaluated, including three fossil fuels, the present nuclear reactor designs, and three advanced nuclear designs. After we examine the strengths and weaknesses of each technology, we will conclude that the advanced nuclear designs offer a path to an electricity generating method that is safe, clean, economical, sustainable, and with a low construction area footprint. The limitations of the renewable power generating methods are contrasted, and we will conclude that some renewable power sources may serve as power supplements if you can afford them. But you must understand their limits. Data will show that there is not going to be 100% renewables for the majority of regions in the world.

We have a bond with energy even if we often don't think about it. That bond ruptures when we are sitting at home comfortable with the world and then it happens! The lights go out along with computers, TV, refrigerator, and clocks. Yikes! A panic grips us when the power goes off for a few seconds or God forbid for an hour or for months. We feel helpless and agitated. There are few more destabilizing events. The power comes back on, so we relax and forget. We live that close to the lion's mouth, such as the Texas cold weather energy disaster in February of 2021.

Renewable Energy Properties

We define renewable energy sources as ones that takes their strength from fuel that is naturally replenished_such as solar, wind, hydroelectric, geothermal, biomass, tidal currents, and waves. Wind and solar renewables are the most mentioned today, and we will analyze why they are limited and what is their role. Logical reasoning can conclude that renewables are not predictable and can't dependably or otherwise power large populations – the sun doesn't shine at night and the wind doesn't blow at strength when we want. You don't need math to figure that out. All renewables have the common property of unpredictable power, need for large land area to achieve high power capability, baseload backup, and cost.

We will use numbers to show the renewable weaknesses when trying to dependably power large populations for 24/7. Solar power varies considerably under clear sky, mild overcast, heavy overcast, rain and snow, seasonal change, and daily power. A wind generator data sheet will show how power generation reacts to a range of wind velocities, and the results are not encouraging for most of the US. Hydroelectric power is the only renewable that can power large populations, but only in selected regions of the US, such as Washington, Oregon, Idaho, Tennessee, and New York state. This information is relevant to the recent public activity claiming to replace fossil fuels by going to 100% renewable energy sources.

Baseload Energy Properties

Baseloads will be with us for our lifetimes, so let's look at them in more detail. Our four baseload choices are dependable, but each comes with a price. Coal emits chemically documented deadly toxins, greenhouse gases, and has mining fatalities. Natural gas and diesel fuel emit abundant greenhouse gases and also have significant mining fatalities. Diesel burning uniquely adds fine carcinogenic soot particulates to its greenhouse gases. Coal, oil, and gas fossil fuels take hundreds of millions of years to form, but we burn them in seconds *never to return*.

The four baseload energies differ in their human and animal death rates, sickness, cost, toxic pollution, greenhouse gas emission, future fuel mining limits, reliability, waste, and design complexity. Business pressures are intense to maintain a status quo, but let's decide what is right and address business concerns later. This investigative journey began with little anticipation of how it would conclude. The conclusions were a surprise.

Fossil fuels provide about 60% of our total US energy. We use fossil fuels because of historical practice, cost, and their dependable 24/7 power. We build large complex energy systems that use fossil fuels. We know how to do it. Natural gas is enjoying a high rate of new gas electric generators, and that is due to a disruptive technology called fracking. Fracking has been sold as a source that has a hundred years or more of life. That time will be challenged in a later chapter in which serious energy economists believe fracking might be a 5 – 15 year bubble. That is one of the reasons we should understand our options with energy sources.

Current nuclear reactors are mostly Light Water Reactors (LWR) that are based on a successful design that was developed for the first US Navy nuclear submarine *Nautilus* in 1954. That 65-year old LWR design has several advantages but also some marked weaknesses. The negatives include the cost of a new nuclear plant, the cost to enrich uranium and repair, passing regulations, nuclear waste, and the unexpected, shortened life span shown by many LWRs currently in operation. These properties suggest that this traditional form of nuclear power generation could see an end of life in the near future. But the current nuclear reactor designs are comparatively “clean” emitting nothing except safe near zero radiation condensed water vapor. That is a huge advantage, but current nuclear reactors have items to improve on.

Two radical approaches among future alternative nuclear designs show promise. One uses the heavy metal thorium, and another called the Integral Fast Reactor (IFR) that uses uranium in a different fuel form. Thorium research began in the late 19th century, and it was compared against uranium as a primary source of nuclear power during the Manhattan atomic bomb project in the early 1940s. Uranium won the historic battle supposedly because uranium reactors generated plutonium which allowed a simpler path to nuclear weapons. It is clear that nuclear reactors are controlled nuclear reactions and atomic bombs are not.

Both thorium and the IFR reactor designs were demonstrated, and they offer a solution to virtually all fossil fuel and current nuclear problems including cost. It sounds too good to be true but be patient. We will evaluate these two advanced nuclear reactor designs in later chapters.

Figure 1 shows an hourly electrical load power generation over a typical 24-hour summer day for the whole state of California. The nights are quiet, but as the day progresses, people, businesses, and industry wake up and demand more power, and they want it quickly. This increase in power demand activates peak and intermediate load generators that use the short reaction time of natural gas, oil, and certain renewable methods, such as wind, solar, or hydroelectric. Peak and intermediate generators are expensive, since the equipment gets partial use and may operate on average only 30% - 40% per year.

Figure 1 shows that the blue baseload is about 60% of the peak. Electrical power generation must deliver what the customer load demands, and power must quickly adjust its output to match the up and down fluctuations of the customer demand. Figure 1 shows that the definition of a baseload is technically defined as the minimum power needed to support the population. But practically we just refer to these energy sources that can deliver dependable power at any time of the day or season, and those are typically coal, gas, nuclear, and oil. Notice that the red line shows that the peak load demand is from 3-6 PM and is unfortunately shifted more than 3-hours after the peak solar noon power output.

Hydropower is a flexible renewable source of electricity since water flow in dams can be controlled relatively quickly to adapt to changing customer energy demands. Hydro turbines have a short start-up time. It takes about 60 to 90 seconds to bring a hydro unit from cold start-up to full load; this is much shorter than for gas turbines or steam plants. When shorter response times are needed modern utilities may use batteries. Hydro power is also essential for those locations that approach 100% fossil fuel free power generation.

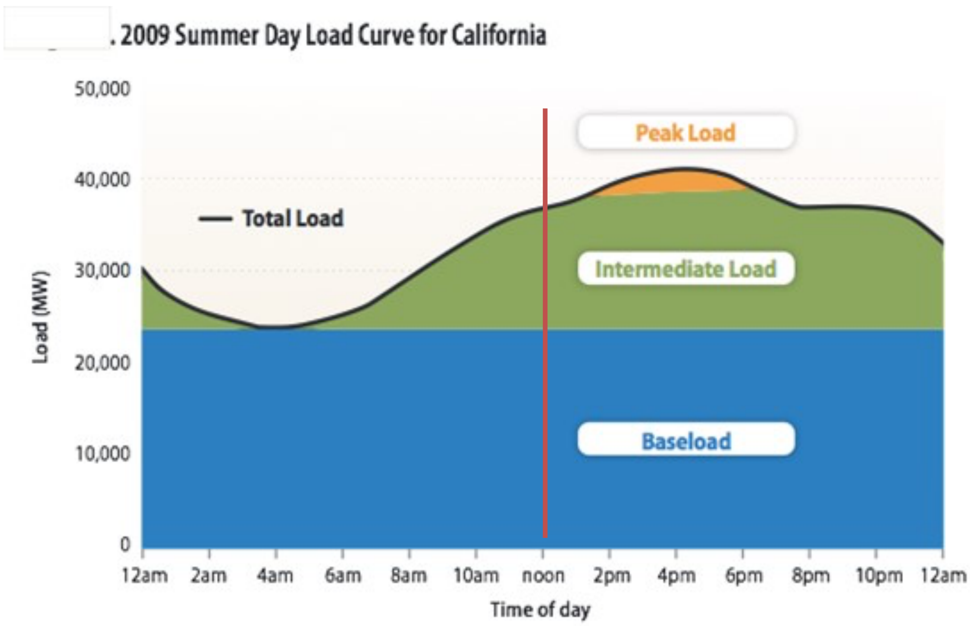

Figure 1. A 24-hour electrical power load curve showing three levels of power generation required. The blue baseload generation cannot be replaced for delivery of dependable power. (From National Renewable Energy Lab –NREL)

Imagining Energy and Power

Our study mixes the words energy and power. Take a moment and scrub your brain of any thoughts. Now, visualize the word energy, and what image comes to mind? Don't image a manifestation of energy turning a turbine, but the pure word energy. What is it? Have you ever seen an energy? The likely answer is that your mind is still a blank. We can imagine steam molecules, photons, or the potential energy of a water reservoir. But we have no image of any of the many forms of energy itself. We know when and where it exists, but its core being is a mystery of the universe. Go ahead, ponder it. Your mind may sink a little deeper, and you know what energy does, but we don't know why, how, or what it looks like.

We use the word energy so often, so let's take a moment to see two of its unique properties. The First Law of Thermodynamics states that energy cannot be created or destroyed, but energy can be transformed to other energy forms. That is a counter intuitive thought as we think that if we burn a coal nugget, we have burned the energy and it will be no more. Not true.

What happens to energy when we burn a pound of coal? We don't destroy the total energy, but watch it convert chemical energy (coal) to thermal energy (steam), to mechanical energy (a spinning turbine rotor), to electrical energy (kilowatt•hours), and to wasted heat energy and a boiler residue called slag. Only now the total collection of energy when you add the heat is the same as when you started with a pound of coal. That energy produced useful work.

Your home may convert electrical energy to heat in your toaster, stove, lights, or clothes dryer. But the waste heat that escapes along the way is still energy that excites atoms and molecules that is a portion of the original chemical energy. Our commercial power generation and electrical distribution follow the First Law of Thermodynamics. We don't burn energy.

But another quirk is that this is a one-way street. We never see mechanical and thermal energy spontaneously go backward such as toaster self-heating with coil energy going backward through transmission lines to create a lump of coal. That is the Second Law of Thermodynamics. All energy forms can "go forward" or "transform forward", or "flow" and ultimately reduce to the thermal motion of atoms and molecules. Literally energy cannot be renewed or recycled despite the acceptance of the word renewable as the label of choice to describe those energies that are free of fossil or nuclear fuel. Despite this mislabel, we are stuck with the word renewable, but that's okay.

Figure 2 sketches an electrical power plant generator, and transmission and distribution lines. Fuel (coal) enters the building at the upper right of the figure and is transformed from chemical energy to molecular kinetic energy (steam), then the energy of steam to mechanical rotation of the magnetic rotor generator, and then to electrical energy. The next conversion is from the lower generated voltage to very high voltage for the transmission lines to the customers. This is all 1st and

2nd Law of Thermodynamics stuff. The power delivered to the lines may approach 40% of what we started during coal burning. It is a clumsy system that Thomas Edison developed about 1894 in Manhattan, New York, and we have clung to it. Energy is not recyclable or renewable. It is what it is.

You might ask that if you charge a car battery with solar energy from your roof solar panel, isn't that a rechargeable action? We've kept a secret from you, and that is where do the solar energy particles (photons) get their energy. The answer is that a hydrogen atom under extreme pressure and temperature 93 million miles away in the Sun accidently smashes violently into another hydrogen atom, resulting in a union or marriage occurring that produces a helium atom. This is called nuclear fusion, and immense energy is released along with a photon that drives most of our energy sources.

A sun-generated photon goes on its randomly directed low-probability travel to Earth and strikes the solar cells on your roof. The first step is the Sun one-way conversion of two hydrogens to one helium, and it is not reversible. The sun lost two hydrogen atoms of fuel. It takes about 8.5 minutes for that photon to leave the sun and hit your roof. So, using the garage solar cells to recharge a battery did not create or renew energy. It transformed energy. What an unusual system just to charge your battery. Where did the sun get its hydrogen energy? Who knows, but we are now becoming one with the universe, and will stop there with this simplistic review.

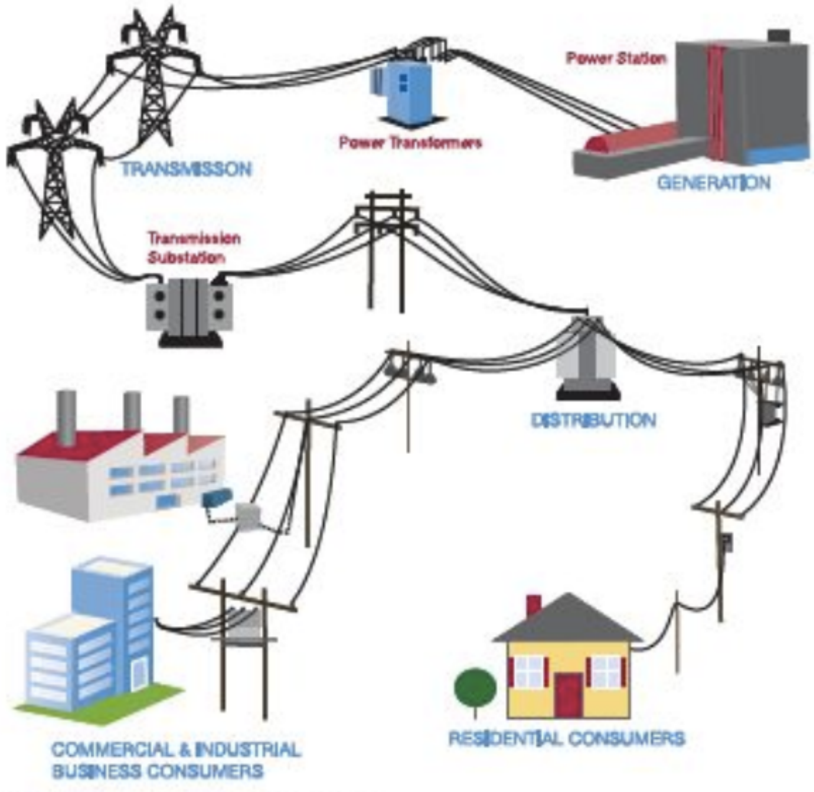

Figure 2. A sketch of a modern electrical power generation and distribution flow [John Kluza, MIT GTM Research].

What is the Problem

The US presently powers its baseload generators with coal, gas, oil, and nuclear that give a mostly dependable electrical power. So, what is wrong with our way of doing business? Or why don't we take the old advice, "Why fix it if it ain't broke?"

Well, by many definitions electrical power is delivered, but the energy system is broken. Coal and oil are finite resources that are unsustainable in the long term if we keep burning them, and they have serious human fatality, health, and climate issues. Natural gas has serious sustainable issues, but in the short term it may be a slightly less damaging fossil source. This is called damming with faint praise. All fossil fuels will run out eventually, and that common sense is what we should keep in mind as we plan for our energy future. And please don't smirk, "Well, I will be dead by then." The 1st and 2nd Laws of Thermodynamics are not going to change to suit our convenience or our mortality.

The American power industry is currently moving from coal to natural gas power generators, but coal companies, railroad companies, and some states such as Wyoming, West Virginia, Kentucky, and Tennessee have a business survival interest in coal. Identifying renewable engineering solutions to these problems may be easy but enacting them can engage strong opposition. It can be especially annoying in our new world where Facebook can bring hundreds of name-calling energy combatants into your home.

Despite clear advantages, modern nuclear energy faces a strong misguided public fear. Yet many scientists and engineers believe a modern next-generation nuclear design is the future energy choice over the fossil fuels. Our position is that all four current baseload generators have serious deficiencies and should be replaced.

What do We Consume?

The U.S. Energy Information Administration (EIA) listed the 2019 US distribution of major electrical energy sources.

38.4%	Natural Gas	7.3%	Wind
23.5%	Coal	6.6 %	Hydropower
19.7%	Nuclear	1.8%	Solar
0.5%	Petroleum	1.4%	Biomass
----------------------		0.4%	Geothermal
		0.4%	Miscellaneous

The four base load generators in the first column are known to be undesirable as we have mentioned, but it is what we have in place, and they are the only sources that deliver large amounts of dependable power. Fossil fuel generators (coal, natural gas, petroleum) supply about 62% of the total electrical energy generated in the US. The renewable energy group in the second column are the rock stars from wind and hydropower on down and are publicly thought to be more desirable. In 2019 wind overtook hydroelectric for the first time. The percentage of gas to coal generators in Florida in 2019 reported 72% gas and 12% coal.

So why is the list not inverted with most of the energy coming from the renewable sources? The latter grouping will certainly grow, but each has walls bounding their ability to scale up and deliver adequate amounts of dependable power to large populations.

Thermal Generator Efficiency Limits

Base load power generators typically use steam or a high temperature gas turbine to generate electricity. The turbine rotates and a magnetic field emerging at the tip of the rotor sweeps across a fixed magnetic field of the copper stator wires outside the moving rotor. This magnetic field sweeping action generates voltage in the wires that transfer electrical power to customers.

Now comes the first of three equations in the book telling us how to approach the turbine efficiency using the simple math of 4th grade subtraction and division. Higher efficiency means using less fuel to deliver power, so this is a big one. A high temperature pressurized steam or gas at a Kelvin temperature *Ts* drives into the front end of a turbine and exits the rotating turbine at a lower pressure and Kelvin temperature *To*. The thermal energy blasts through the turbine where some of the energy is transformed into the work of rotating the blades of the mechanical rotor. Another part of the energy is transformed into waste heat that doesn't drive the turbine. In 1824, Carnot derived the efficiency η of a heat (steam or gas) engine using Kelvin temperature.

$$n = \frac{Ts - To}{Ts}$$

It is a theoretical prediction of how much useful work you can g**et** from a heat engine whether it drives a ship, a jet engine, or an electrical power generator. The equation relates the temperature or pressure difference across the turbine and not on energy wasted on support components of the plant generating system. It took years of deep thinking to finally write this little old equation, and we use it constantly almost two hundred years later. It guides our energy selection process.

For example, for a pressurized steam temperature of *Ts* = 826 K (550^{o}C) and a turbine output of *To* = 298 K (25^{o}C), the efficiency is 64%. Overall power plant losses must include the energy to pressurize and raise the boiler temperature. Boilers, temperature converters, steam pipe thermal inefficiency, transmission lines, and mechanical moving parts reduce overall efficiency to about 35%. Typically, 65% of the original energy content is lost as unused waste energy. The equation instills the fundamental turbine design goal that a hotter input and a colder output elevate fuel efficiency. That is the takeaway.

The design objectives taken from the equation are enacted when we put the steam boiler hot side of the turbine under high pressure to raise the water boiling point. Steam forms at 100^{o}C at atmospheric pressure, but that is too puny for electricity generation. But when water pressure is increased, then the boiling temperature rises and this simple trick increases steam temperature *Ts*. A modern steam boiler can deliver pressures up to a whopping 2,200 psi and steam generation temperatures up to 320^{o}C. The high-pressure steam has an efficiency advantage but can be a product weakness. Major accidents arise from steam explosions when temperatures and pressures inadvertently rise out of control.

Another century's old design trick injects cooling water into the turbine output driving down the exit temperature *To*. The steam condenses creating a strong vacuum, and the pressure *Po* drops by a factor of about 60. Exhaust cooling is a heavily practiced technique that began with the steam engines of the 18^{th} century [1]. It is the main reason why steam driven generators need a steady influx of water from rivers, lakes, or oceans. If buildings and houses are near to the plant, then the waste heat can be conserved and piped to warm these structures in a process known as co-generation.

A typical large power electric plant generates about 1 GW -a billion watts that can power about 1-million homes. Multiple generators can be co-located at one plant site and provide total power of over 6 GW.

Odds and Ends

There is so much human behavior and bias confusing in what should be a data-driven analysis of energy sources. The *New York Times* reported in February 2014 that the major issue in an important election in Japan was whether candidates supported or opposed nuclear reactors. The nuclear power issue is complex, and few voters have the time, background, or interest to study it. The voters had mixed feelings after the Japanese tsunami nuclear accident at Fukushima Dachii in 2011. Opinions are cheap and easy, but not worth much if they are not data backed. That doesn't happen in a public opinion poll, and unfortunately that may be the new reality.

Why are nations so driven toward energy? There are many answers, but a country cannot maintain or grow economically or be militarily secure without abundant cheap electrical energy. China is a good example. In about 30 years China grew from a rural society to a manufacturing and science society that rivals the world. Their factories would not exist if stable electrical energy had not been available 24/7. Coal is their most accessible energy form, and they use it mostly without guilt but certainly with adverse consequences.

We take energy for granted in the US but know that the country would weaken if energy were not so abundant. There are power-limited islands in the Caribbean that divide their island into quadrants with each sector allotted only six hours of power per day. You can't run a competitive manufacturing operation on limited power. Electrical energy is favored because it can be delivered to virtually any location in quantities from microwatts to megawatts like no other energy form.

Patrick Moore is a former Green Peace International founder and President [2]. Green Peace took a strong anti-nuclear position that Moore later refuted, and he left the organization [2]. His book titled "Confessions of a Greenpeace Dropout" describes Moore's position on nuclear power as being the only baseload that can safely reduce the greenhouse gas emission problem.

Rhodes mentions nameplate power and capacity factor. These essential concepts are explained in Chapters 2 and 3 as well as the terms Power Density Function and Energy Return on Investment (EROI). These are four simple renewable measurements that allow an engineering judgement.

There is a rich resource of people who speak out on the issues. We owe much to a large collection of quality authors, YouTube speakers and tutorials, and Internet browsers. The Thorium Energy Annual Conference (TEAC) provides all of their speakers on YouTube.com for each conference.

"

Here is a quote from the Richard Rhodes book Energy. pages 330-331 [1].

In 2016 total installed wind electrical capacity reached 487 gigawatts. That's much less than 1 percent of world total electricity. Numbers for these intermittent energy sources are misleading, however, since they represent installed 100% capacity rather than actual energy generated. Their "capacity factor" – how much of the time they generate electricity – is a problem for all intermittent energy sources. The sun doesn't always shine, nor the wind always blow, nor water always fall through the turbines of a dam. In the United States in 2016, nuclear power plants, which generated almost 20 percent of US electricity, had an average capacity factor of 92.1 percent, meaning they essentially operate at full power on 336 out of 365 days per year. The other 29 days they were taken off the grid for maintenance – not all at the same time, of course. In contrast, US hydroelectric systems delivered full power 38 percent of the time (138 days per year); wind turbines, 34.7 percent of the time (127 days per year); and solar PV farms, only 27.2 percent of the time (99 days per year). Even plants powered with coal or natural gas generate electricity only about half the time."

I are indebted to Professor Keith Rambo of the University of Florida ECE Dept. who provided encouragement, advice, and lecture opportunity in his Power Engineering classes, Jerry Soden of Sandia National Labs who contributed his Electrical Engineering experience including renewable power, Paul Collette (40-years with Westinghouse power products), Michael Wright (Power Grid Engineering Corp.), Michael Pears a British power engineer, Jaume Segura of the Physics Dept. at the University of the Balearic Islands who gave me the opportunity to start the work, Shannon Hawkins of the Boeing Corp., Sharan Kalani the Fermilab, the US Energy Information Administration (EIA), the National Renewable Energy Lab (NREL), the World Nuclear Organization, the World Health Organization, YouTube, and the many nuclear, gas, and coal engineers, physicists, and technical writers who pass along their knowledge.

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Chapter 2

Solar PV Renewables

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Distinguished Member of
Technical Staff

There are four important renewable parameters; Nameplate, Capacity Factor, Power Density, and Energy Return on Investment (EROI) that form a bedrock for understanding the use and misuse of renewable energy claims. The Nameplate and Capacity Factors are parameters discussed in the next two chapters, and power density and EROI later.

Solar Cell (Photovoltaic) *Nameplate* Power

Nameplate power is the output power under best conditions for that energy source. Nameplate is the power wattage number that you bought at the store. This section will illustrate the use and misuse of Nameplate values with four solar systems. The first solar system example is a residential 10 kW system, the second system is a is a large 2.25 MW panel of solar photovoltaic solar cells atop a parking lot roof, the third is the German country solar output, and the fourth is a small 800 W system to supply 100% solar to a single room Hogan on the Navajo Reservation in New Mexico.

1. A Simple Solar Cell

Figure 1 shows the near perfect electrical output of a 10 kW residential solar panel on a clear day in New Mexico. 10 kW is the nameplate power rating for this panel. Importantly, the 10 kW nameplate value occurs only around high solar noon. Significant but reduced power output occurs for 4-6 hours around high solar noon depending on the season, the weather, and the latitude. In the far north, the sun may last 24 hours in the summer and zero hours in the winter, but the nameplate power is a constant number. The significance of nameplate number is that it is often misused when reporting the contributions of a renewable generator. When you buy a 10 kW nameplate solar system, you don't get 10 kW but for a few minutes at solar high noon. You can't credit 10 kW as your renewable power generation as many do. The yearly percent on-time or equivalent full power time for this New Mexico system was measured at 23%. And that is a relatively high number.

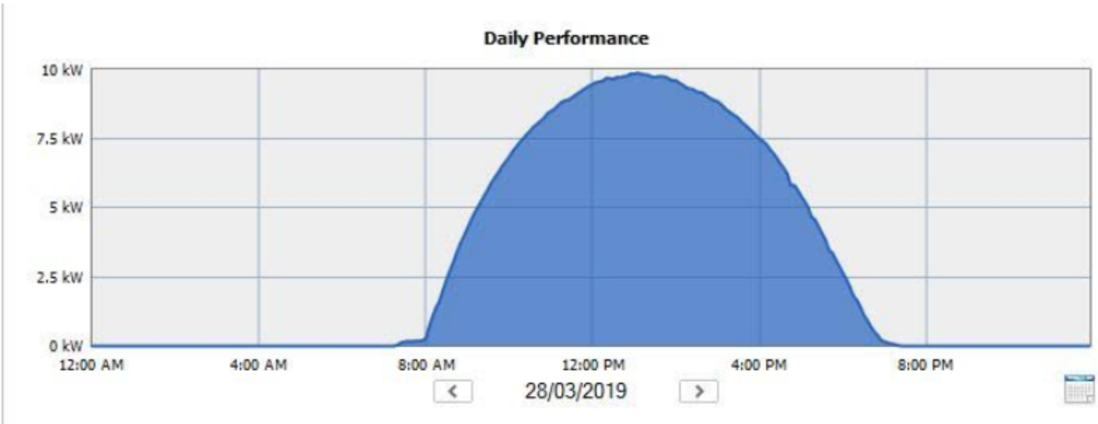


Figure 1. 24-hour electrical output of a 10 kW solar PV array in a high desert environment at an altitude of about 6,000 feet on a March day with no cloud or tree obstruction. The peak value is slightly below 10 kW. But during a cool day a week later, the maximum power went slightly above 10 kW. Notice that solar high noon is about 1 PM due to the solar system high noon is on daylight savings time. The data were taken close to the solar spring equinox where daylight hours equal nighttime hours. (Jerry Soden, Sandia Lab)

Figure 2 shows the effect of passing clouds on the solar panel array (yellow) for the same panel array measurements taken a day earlier in Fig. 1. The power output did not go to zero during this day, but it is markedly and randomly reduced. The density of the clouds affects the power degradation, and an overcast sky can often drive the power output to 10% - 15% or less. A takeaway is that solar energy is always changing, sometimes rapidly.

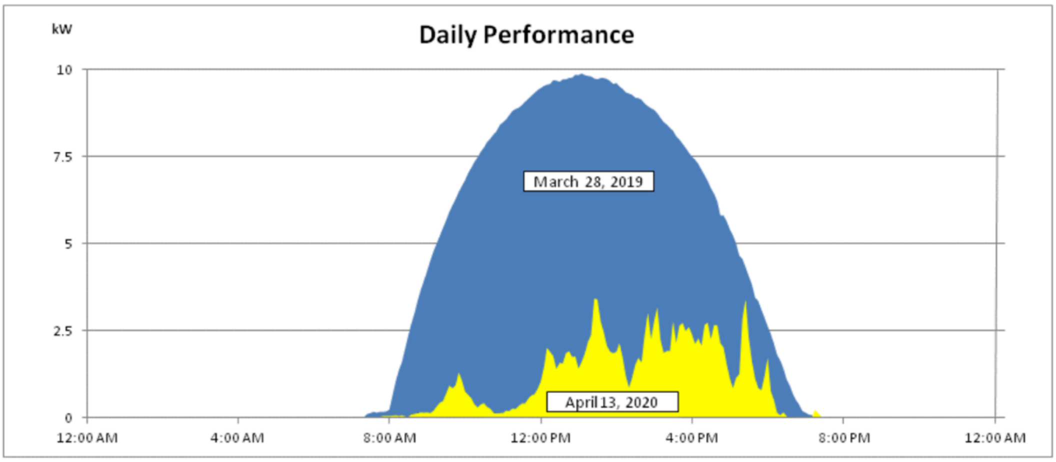


Figure 2. The effect of clouds across a solar panel (yellow color). The blue is the response on a sunny cloud free day. (Jerry Soden Sandia Lab)

Figure 3 shows the solar response on a rainy overcast day. The peak power is expected to be 10 kW at high solar noon on a clear, sunny day. In fact, the lowest power output occurred during a heavy rainfall at about solar noon. The power in Figure 3 shows a spike at 7.5 kW with most solar output below 2 kW. Solar power generation efficiency can be markedly reduced in rainy states such as Florida and Washington.

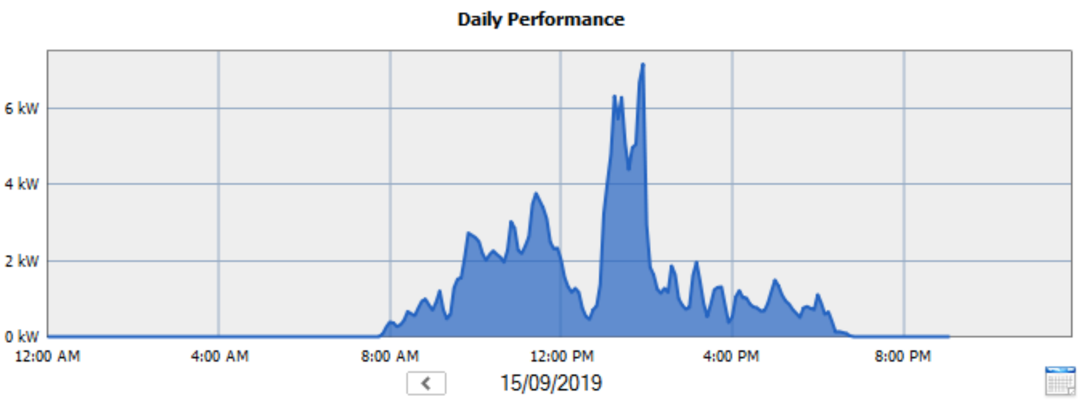


Figure 3. The effect of a heavy rain on a 10 kW solar panel. (Jerry Soden Sandia Lab)

Figures 1-3 show the profound limitations of solar renewables. Solar PV systems can ideally deliver close to 100% of nameplate power for less than an hour on a clear day. Typically, municipalities or utility companies report only the solar nameplate number, and this predicts an erroneously higher power than what the solar system actually delivers. On a sunny day, cumulus clouds can take up more than 50% of sky and seriously affect solar energy production

Figure 4 shows the annual solar regularity over a 2-year interval as a solar system responds to the changing solar irradiance and weather. Passing clouds and rain or snow can cause the spikes in output power. PV solar systems do supply clean power, but it is not enough to support a large population and replace baseload power. The baseload power source must also provide a power backup equal to each nameplate renewable power source. The data presented in Figures 1-4 were measured by an experienced electrical engineer, and the results should be burned into your brain. This is the was solar renewables respond.

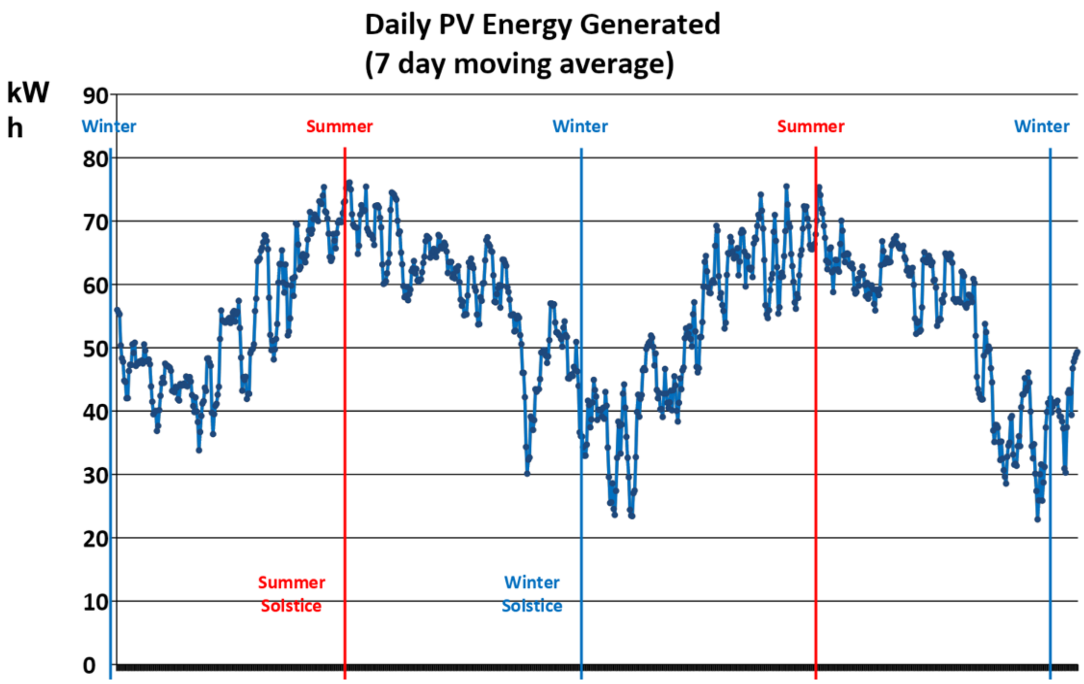


Figure 4. A 2-year record kWh of the solar output from a PV system in New Mexico. (Jerry Soden Sandia Lab)

Figure 5 shows the total solar output in high latitude Great Britain for 30 days in September 2019. It produced 30 solar energy pulses correlating with daily sunlight intensity and clouds. The variable height of the solar pulses reflects daily changes in sun radiation reaching the solar panels. The solar outputs are not constant nor predictable. Weather forecasting is used and to help approximate daily solar power. The impact is on the baseload power needed.

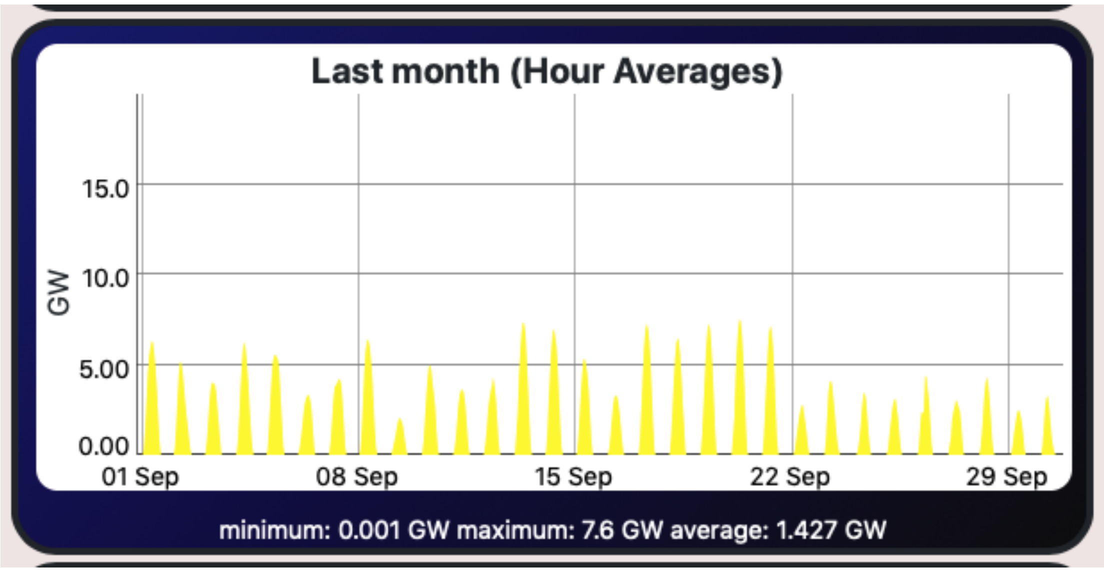


Figure 5. Daily solar energy production in the United Kingdom in September 2019.

https://gridwatch.co.uk/Solar

These solar panel response figures help visualize the dynamics of a solar panel. Its power output is not steady, can change rapidly and unpredictably, and it is at nameplate rating for only a short time during the day, if at all. Nameplate values should not be used to report the real power output of a house or utility. It is a common error.

When an overcast day or rain or snow reduce solar radiation intensity on the panels, the solar panel still generates power, but it is reduced. Rain and snow more significantly reduce the power output. Accumulated snow on solar panels can reduce their output to near zero. Chris Root is the Chief operating Officer of the Velco Corp.in Vermont. He reported an extreme weather event that snowed for five straight days. The solar output of a 20 MW solar farm was not 20 MW but zero for these five days. The utility company had to have a reserve capability to make up for the undependable solar system.

The electrical grid must also absorb the rapid change to the system of a passing cloud that rapidly lowers and then elevates the solar power. A 50 MW solar farm may drop in seconds to 10 MW-20 MW and then return to 50 MW after the cloud passes. Most power plants can handle thousands of perturbations of renewable energy contribution, but millions of inputs can overwhelm and destabilize the system [1,2].

There is a strong bond between renewable energy and baseload energy. That doesn't make sense, since we thought that a reason for using renewable energy was to reduce or replace baseload power generation that uses fossil fuel energy with a renewable source. Painfully it is not so simple. A baseload generator of equivalent wattage *must back up the* unpredictability of renewable energy sources. When solar or wind aren't generating electricity what do you do? You must have a backup and that is a baseload. Most solar PV rooftop homeowners use their local power company as a storage for backup. That's a bummer but true. A nameplate 50 MW solar farm must have a 50 MW backup of the baseload to match the maximum PV renewable power. That backup can be coal, gas, or nuclear.

A magic *energy storage* device to store renewable energy that can support large population gigawatt loads for days or months remains out of reach. Hydrogen gas is mentioned, but it is explosive, and its tiny molecules are eager to leak through small cracks and valves. We are for the present hopelessly married to a mix of baseloads and renewables. Renewables do reduce greenhouse gas emissions, but their limitations are not widely known to the public.

2. A Parking Lot Rooftop Solar System

Rooftop solar panels have side benefits such as allowing cars to park in the shade, and the asphalt surface is shaded and does not reach sunlight temperatures of near 150^{O}C (Fig. 6). A 17% solar power delivery means that the factory uses the grid 83% of the time. In its defense though, the factory needs peak daytime power for motors, air conditioning, computers, and lighting. This demand is greatly reduced at night.

Figure 6. The parking lot solar system at the Lockheed-Martin Corp. facility in Oldsmar, Florida. The photovoltaic panels have a nameplate of 2.25 MW costing \$5 million. The percentage of time that the system produces nameplate power per year is called the capacity factor and it is 17%.

The sky in the background of Figure 6 shows a common Florida warm temperature feature of beautiful dense cumulus clouds. In fact, just below the sunshine on the land, we see shade from a passing cloud that also shades the solar panels. That can cut the 2.25 MW power in more than half. This region in Florida places a premium on trees that are beautiful but also shade the houses in the hot summers. The trees also block the possibility of residential solar systems.

The normalized cost to the million watts is $\frac{\$5\ M}{2.25\ MW} = \$2.2\frac{M}{MW}$.

That is costly, but we will compare it later with a single room 100% solar system.

3. German Solar Power

Germany is an example of heavy investment in wind and solar. On June 6, 2014, German claimed that 50% of the nation's energy came from solar. That's impressive, since for only another 50% it would seem that we can get 100% solar for a large industrial country -not so fast. The truth is that the data are for one day on June 6, 2014 at solar high noon when it was true. By the late summer afternoon, it was not true. The solar contribution was basically finished for the day until it slowly began increasing the next morning. And on subsequent days and months, it was not true.

Figure 7 shows the German 2014 total solar electrical output for each month. Solar output is highest in the summer months of May, June, and July, and miserably low in the winter months. Another take-away is the erratic, unpredictable, day-to-day solar output even in peak summer months. To that we add cost, the inability to scale up, the need to power large populations, and requirement of baseload backup are five major weaknesses of solar. The peak solar power was uniquely and temporarily above 8,000 MW around June 6. You can see that point in the June curve.

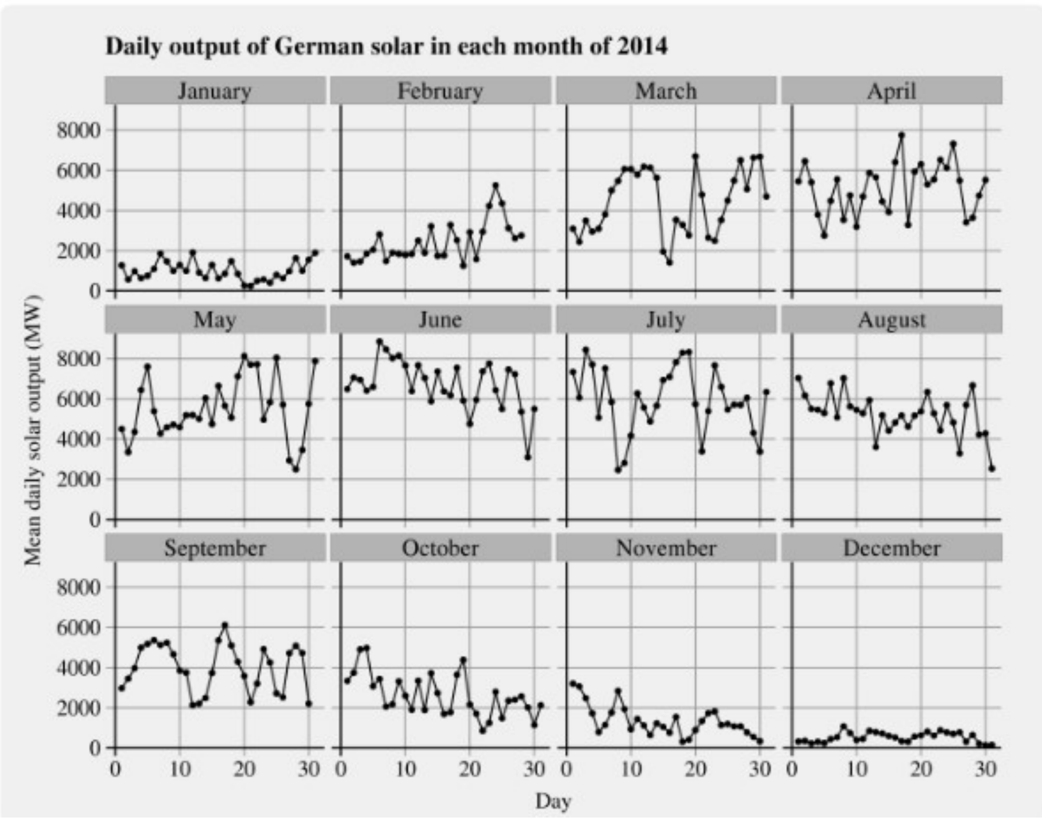


Figure 7. The erratic solar production in Germany during a full year. https://carboncounter.wordpress.com/2015/08/11/germany-will-never-run-on-solar-power-here-is-why/

The German solar contributions are quite low from November to March, and in December-January, and the average solar power delivered in Germany during solar high noon was close to 1%. The winter sun sits low as it slides across the southern horizon from 9 am to 4 pm, and then there are the issues of cloudy, stormy weather. In 2014, 5.7% of Germany's yearly total electricity generation consumption came from solar panels not 50%. Solar energy has been referred to as sunny day electricity.

Germany has slowly installed renewable power generation since the 1990s. It now ranks third in the world in total renewable investment. Recently, solar and wind investments have dominated the renewables. Table 1 lists the wide diversity of German electric power sources in 2017. The units are in billions of kWh per year which implies measurement of actual power delivered. Onshore and offshore wind contribution is 13.3% + 2.8% = 16.1% plus solar power at 6.1% gives a total contribution of 22.2% of total wind and solar power. That is in the face of large investments. The total renewable share in 2017 was 33.1%. These are reality numbers for the advocacy of 100% renewables. The dirty lignite coal increased from 17% in 2017 to 22% and nuclear dropped 3% from 2017. These are troubling data since greenhouse gas increased for both actions. Notice that the comma in the Table 1 numbers is the European symbol for the decimal point.

Table 1. German Energy Sources (2017, Wikipedia)

Energy Source	% of Total Power	billion kWh
Lignite	22,6 %	148,0
Nuclear	11,6 %	75,9
Hard coal	14,4 %	94,2
Natural gas	13,1 %	86,0
Others	5,2 %	33,4

Renewables	% of Total Power	billion kWh
Wind onshore	13,3 %	87,2
Wind offshore	2,8 %	18,3
Biomass	7,0 %	45,5
Solar power	6,1 %	39,8
Hydropower	3,0 %	19,7
Domestic waste	0,9 %	6,0
power generation [gross]	100 %	654,2
renewable share	***33.1 %***	*216,6*

We can see the increase in renewable contributions over a three year period from 2017 to 2020 in Table 2. The total power consumption of Germany in 2020 was 532.3 GWh an increase of 11% over 2017. Wind share increased about 39% while solar increased 21%. Offshore wind is a bit more efficient, since there are no obstructions in the water to weaken the wind and create gusts. But the cost of an off-shore wind generator is about four times that of on-shore wind generator. Imagine a ship that can carry and attach a 35-ton single wind blade to the generator tower in a wave environment. Only about four ships in the world can do this.

Hydropower and biomass were flat. Biomass is an odd ball. It can mean cutting trees or growing maize in a large agriculture field complete with fertilizer and farm equipment. Proponents of biomass argue that the trees and farm foliage absorb CO_2 that neutralizes the CO_2 released during the burn. That is an imperfect argument, since biomass emits some pollutants, and the daily trucks carrying the fuel pollute the air. Biomass is a clumsy process especially when more efficient power generation is shown in the nuclear sources.

Table 2. German Renewable Energy Sources (2020, Wikipedia)

Energy Source	% of Total Power	Billion kWh	Increase Factor 2017-2020
Onshore wind	18,7	103,3	1,41
Offshore wind	7,7	27,5	2,75
Biomass	7,2	44,1	1,03
Solar	8,9	50,4	1,46
Hydropower	3,3	18,5	1,10
renewable share	**45,8%**	**243,8**	**1,37**

The price of electricity in Germany is about 33 cents per kwh, while the price of electricity in Florida is about 11.4 cents per kwh. Also, the German carbon emissions have not dropped when nuclear was replaced with lignite coal. The strong investment into renewables has unfortunately not happened.

The lesson is that Germany's experience is what we see from renewable properties. We will never approach 100% power for large or medium populations using unreliable renewables. The next chapter describes how certain locations in the world can approach 100% fossil fuel free power. But the 33.1% and 45.8% renewable percentage in Table 1 and 2 is to be carried in our brains since it represents the result of a major effort to reach 100% renewable power in a large population.

(4) A Simple Example Of 100% Solar Power Generation

100% renewable power can be attained with a small population, but it requires expensive batteries to store daytime power for nighttime use. The Navajo Nation in Western New Mexico supported a project to provide 100% solar power to some of its hogans, the name for a single room family dwelling that serves to feed, power a refrigerator, sleep, and have space for TV.

Figure 8 shows construction site at one of the 800 watt systems on a cold day in February at an altitude of 8,000 feet. The 800 Watt system uses six NiCad batteries at a price in 2007 of $500 per battery to store daytime power and deliver when the sun went down. A low power refrigerator was needed to avid the power drain of an inexpensive one. The total cost of this simple system was about $20,000. That is an exuberant cost at a normalized ratio of $25 million per MW, but there were no other options for off grid support. That is about eleven times more costly per MW than the parking lot roof top solar system of Lockheed-Martin.

These off-grid dwellings could finally refrigerate food and medicine. The occupants had to conserve power when the sun went down, but it worked. The cost included the expensive special low power refrigerator and the expensive batteries. Solar power delivers 100% fossil free power, but the cost and limited power illustrate why solar cannot power larger populations.

New Mexico has over 300 cloud -free days, relatively low latitude, minimum number of trees, and high altitude. This is as good as it gets for solar power. Alaska has many winter days when there is no sunshine. Hopefully we didn't scare you away from solar with these facts. What it says is important, and you have seen that these data weaken a false claim by enthusiasts for 100% renewable energy. Remember you can love renewables; but they can supplement and don't replace baseload fossil fuel or nuclear use.

Figure 8. Installation of a small 800 Watt solar panel for a Hogan at the Ramah Navaho Reservation. The project was done with the student club at the University of New Mexico called Engineers Without Borders.

Cloud Cover and Solar Irradiance

The weathesprrk.com web site is essential to estimate a major force that reduces solar panel efficiency. You can find a dozen yearly weather plots in most towns and cities such as wind speed, wind direction, rain, solar irradiance, cloud cover, daylight hours, and temperature. Figure 9 shows NOAA cloud coverage data averaged for 35 years from 1980 to 2015. The beautiful summer cumulus clouds and frequent rain have a major impact on solar efficiency when air conditioning is at its peak demand.

Figure 10 shows the yearly averaged data for solar irradiation for Safety Harbor. It shows that the winter solar energy irradiance in about 50% lower in the winter than the summer. .

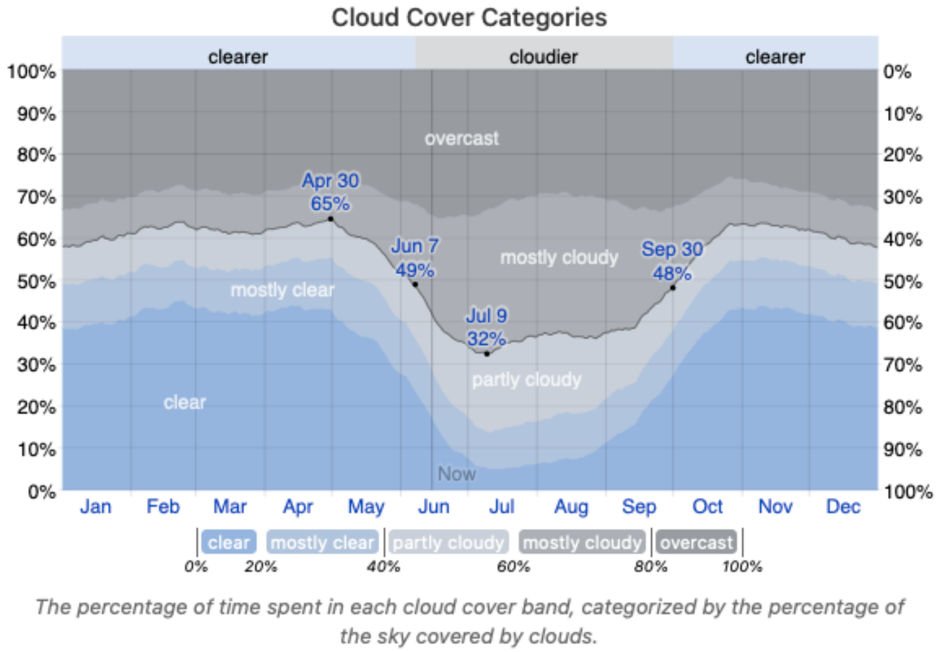


Figure 9. The averaged yearly cloud cover data for Safety Harbor. Florida , a small town located on the shore of Tampa Bay.

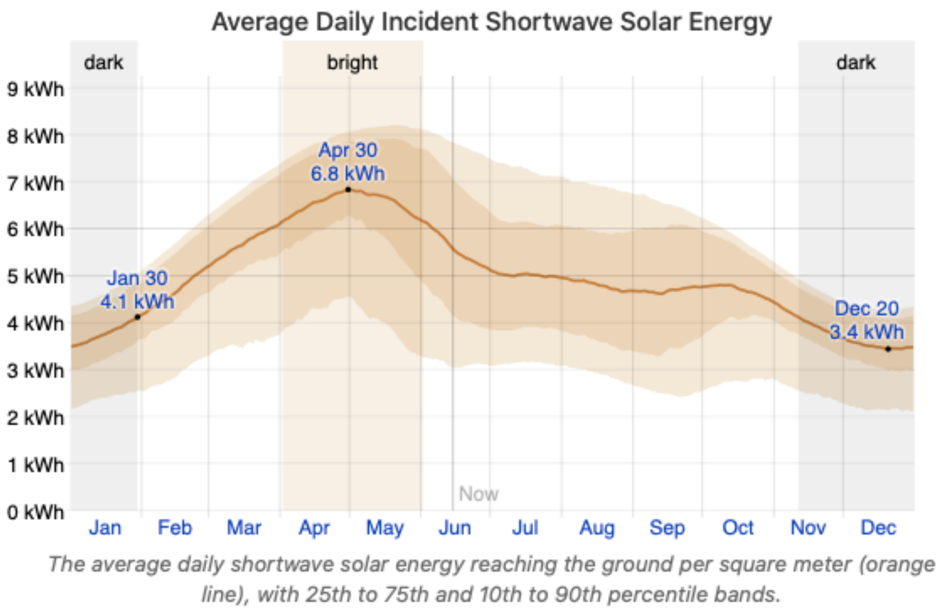


Figure 10. The averaged yearly solar irradiance data for Safety Harbor. Florida,

The choice of weather data in Safety Harbor can vary with geographic location, but local data can be better or worse. But virtually all sites examined showed the same weaknesses as Safety Harbor.

Capacity Factor -The Energy Percent On-Time

Capacity factor is a parameter of all renewables. It gives an estimate of what percentage of time that a solar system can reach perfection of delivering the nameplate value 100%. It can't and that is what capacity factor tells us.

A Solar PV system output is naturally absent from late in the afternoon to the next morning. As a rough estimate, assume that the solar panel produces significant power from 10 AM to 3 PM. That five hour interval represents 5/24 = 20.8% which is a simple approximation of the on-time, or capacity factor for a day without clouds. It neglects the lower power output on the two edges or the seasonal variations. A better value would average over many days such as a year, and that would incorporate the time varying effect of clouds, rain, and solar irradiance for a full annual cycle. The capacity factor is useful to evaluate an energy source based on how much time it is actually generating power. That real output is a parameter measured in kWh as kilo watt hours.

Oldsmar and Orlando in Florida are 90 miles apart but have about the same latitude and weather. The capacity factor of the Lockheed-Martin Corp. 2.25 MW solar system and a residential 10 kW system in Orlando were both measured at 17%. The high altitude New Mexico with more cloud free days measured a solar capacity factor of 23%.

A simple example will show how capacity factor is calculated. You need only two numbers and they are the nameplate of your system and the total kWh for the year as measured by your power meter.

Example 2-1. The total power delivered from a residential 10 kW solar panel in a year was measured at 15,768 kWh. The nameplate maximum kWh for the system is

$$10\ kWh\ x\ 8760\ \frac{h}{year} = 87{,}600\ kWh$$

$$Capacity\ Factor = \frac{15{,}768kWh}{87{,}600\ kW} = 18.1\%$$

It is a simple calculation that tells us a great deal about the power delivered as referenced against the total power if the nameplate energy ran at full capacity for a year. It is an essential, simple parameter to assess what you ae actually getting. Capacity factor drops when passing clouds, shade form buildings, trees, latitude position, time of year, or weather is a factor. It is also a factor when a hydroelectric dam reduces water flow at night when demand is low. But for hydroelectric dams, that lower number is intentional. Communities that clam their out power must include the nameplate and the capacity factor data. Too many communities often report only the nameplate value, and the real power output may be 10% to 15% of that number.

What Have We Learned?

Residential solar owners are mostly happy with a system that reduces monthly electric bills even though state legislators have typically capped home solar nameplate at 10 KW or even lower as in Illinois at 7.5 kW. Power company lobbyist battle to lower tax breaks for residential solar power generators. Utilities have a case in that they supply the power lines, provide backup for renewable down time, and Hawaii and California report system instabilities when too many solar PVs are pouring current back into the grid. So residential solar power is not the solution to reducing fossil fuel emissions

What about large solar farms that have nameplates values in the tens of MWs such as a 50 MW solar farm? They often include advertising that is based on this nameplate, claiming that the farm will supply power to so many homes. The solar farm will supply power to homes but at maybe an average of 10% of the nameplate number.

It is critical that we understand the limitations of the large solar farms. They are expensive, and they take acres of land. The Ranger Power Company builds large solar farms. One in Flint, Michigan takes 2,000 acres, costs $250 million and generates a nameplate of 239 MW. A second farm in Montcalm County takes 2,200 acres, costs $200 million, and generates a nameplate of 200 MW. None of the announcements mentioned nameplate and capacity factor or the impact of taking thousands of acres. Michigan is notorious for having constant overcast skies from March through April.

The 2.25 MW parking lot roof system in this chapter had a capacity factor of 17%, and while it suits daytime power needs of the plant that doesn't compensate for cloud cover, rain, and solar irradiance reductions. This is not even close to be considered for 24/7 power delivery to large populations.

The daytime power output of the solar cells presented in this chapter say it all with respect to reducing solar time to deliver power and the crippling effect of clouds and precipitation. Sunny day cumulus clouds are prevalent in most states taking a toll on the nameplate value. The German energy data in Tables 1 and 2 are strong showing that in 2020 combined solar and wind renewables combined for only 35.3% of total power.

What about batteries to store power to distribute during the solar off time? That 800 W system worked and gave 100% renewable power to the one room Hogan home for the Navajo Tribe using six $500 all-weather batteries. It proved a point, but the system was about as small as you can get, and it was expensive. The recent Tesla Li-ion batteries are found in another application with a utility plant to store and reduce peak load and to more precisely adjust grid parameters. The batteries can be used with solar farms, but again require many batteries that may be $1,000 a piece or more. Picture the Li-ion frame as the size of a car battery. A Tesla car battery array weighs about 3,000 pounds. Advanced nuclear designs offer a simpler, cheaper solution.

We summarize that solar photovoltaics are not appropriate to serve large populations. They have problems with unpredictable delivery and are geographically specific. Now, let us exam wind generators.

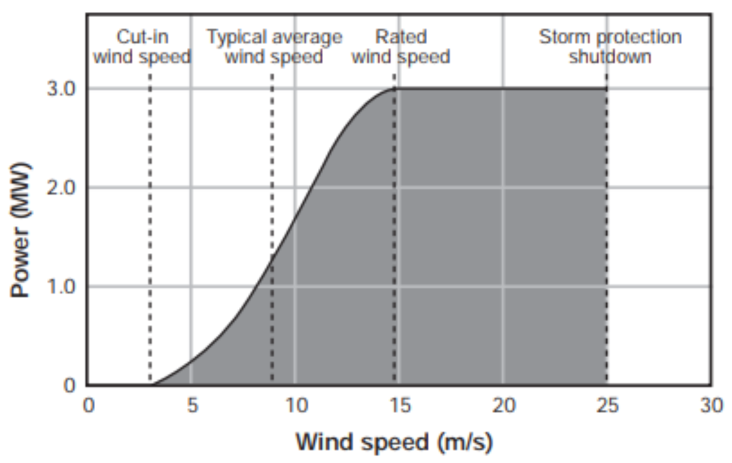
Chapter 3

Wind Renewables

Wind Generator *Nameplate*

A wind generator also has a nameplate power rating that is the power under ideal wind conditions (Fig. 1). The wind must directly strike the blades at a 90^{O} angle at a steady velocity. If the wind speed achieves a velocity more than 40 - 55 mph, the generator shuts down for protection. Blades can shatter from centrifugal force at high winds, or the generator-rotor section called a nacelle can overheat and catch fire. Notice in Figure 1 that if the wind is less than about 3 m/s (6.7 mph), the blades don't turn, and the power curve shows no output. It takes about 9 m/s (20 mph) wind to get the wind generator output up to 33% of its nameplate of 3 MW, and it takes a 25 mph wind to get up to 67% of its rated value. Some parts of the country in the West and Midwest may typically have a high percentage of steady winds but most do not. The cost of a 3 MW generator is about $6 million.

POWER CURVE OF 3-MW TURBINE V90 WITH WIND SPEED CATEGORIES



SOURCE: Vestas 2007.

Figure 1. The power output curve of a 3 MW wind generator. The number conversion of m/s to mph is 2.2. The nameplate voltage was measured at a wind speed of 15 m/s (33 mph). 10 m/s (22 mph) is labeled as an average wind speed. That would put the output of the Danish Vestas Company generator at 1.2 MW/3 MW = 40%. The wind turbine levels off above 15 m/s (33 mph).

When the wind varies markedly around any point on the curve, it drives the power output up and down the curve as wind gusts come and go. Wind generators can reduce the noisy effect of individual generators by connecting the outputs of many generators. An expensive cure is to connect the outputs many farm wind generators with 20 – 200 generators on the farm. This averages out the random erratic output as simulated in Figure 2

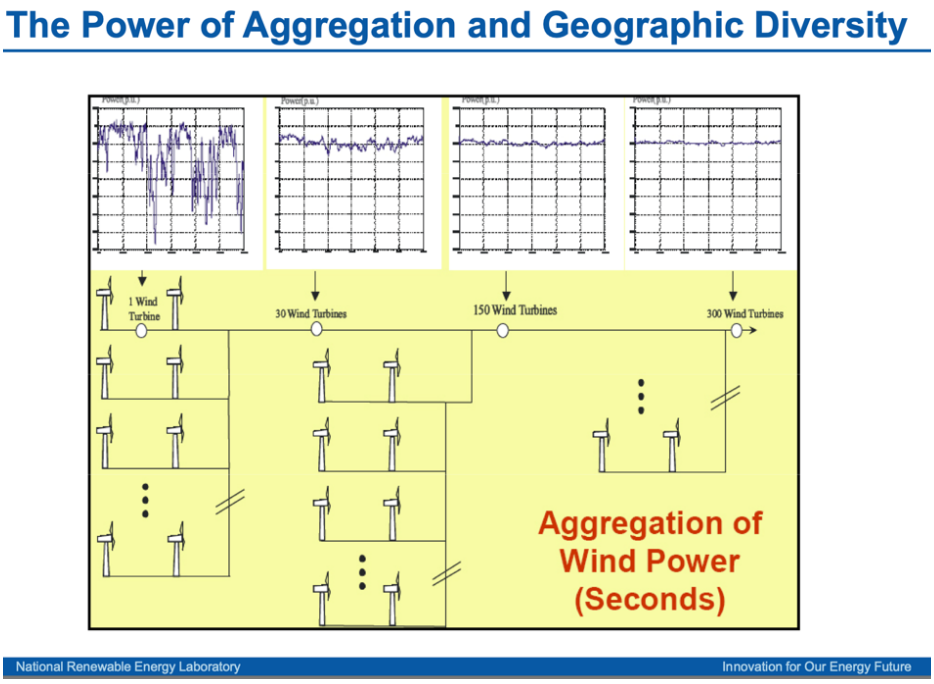


Figure 2. The signal smoothing effect of connecting the random output of many wind generators. [NREL]

Wind meteorology defines the first approximately 300 feet above the ground as the Boundary Level. Above the boundary height, the wind flows in a relatively gust free pattern. The gusts down lower are cause by interaction with trees, homes, building, and hills. Look higher and watch the steady flow of clouds compared to the ground turbulence. This is why offshore wind generators have quiet reduced gust and better efficiency.

Figure 3 shows the NOAA weatherspark.com average weather wind speed data from 1980-2015.

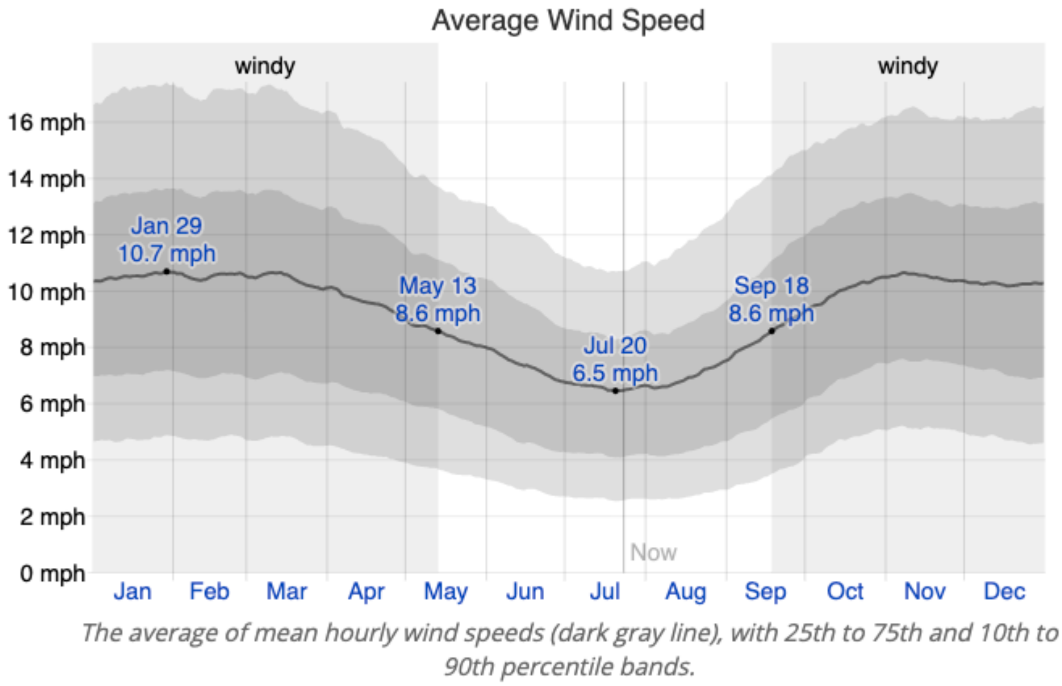


Figure 3. The 35 year averaged wind velocity in Safety Harbor, Florida.

Figure 4 shows the total wind generation data from West Texas measured by the Electric Reliability Council of Texas (ERCOT). It shows the unpredictable nature of wind generation (lower blue line). Coal, gas, nuclear, and oil are predictable, and our electrical system demands that. The erratic power generation of wind can supplement a power station during peak hours and that is a good thing. But for 24/7 public use, power must have a constant platform.

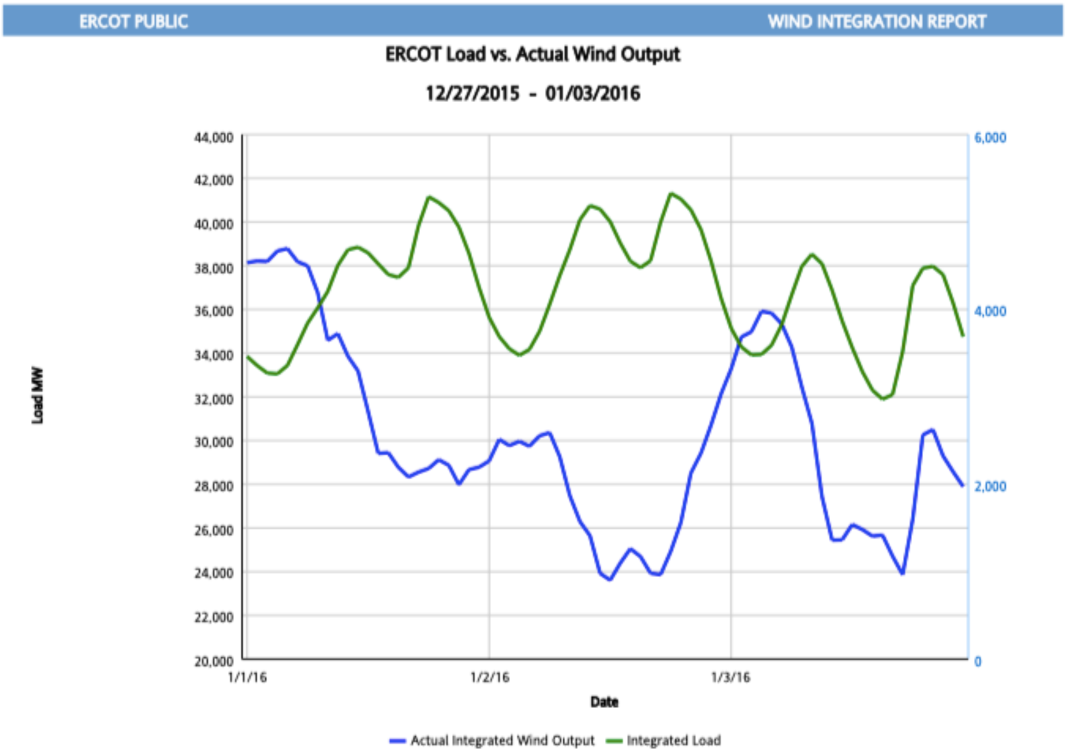


Figure 4. Six-day curves of wind farm generated power (blue) and customer power demand (green). Power is in MW. The curves show that demand and wind power were not synchronized. In contrast, some climates can roughly correlate day time air conditioning and industrial demands with available solar energy. [mis.ergot.com}

Wind and solar seem perfectly safe, but the reality is that there are injuries and fatalities. The Caithness Wind Farm Information Forum reported that in England in 2011, there were 163 wind turbine accidents with 14 fatalities. Nearly 120 wind turbines catch fire each year (https://www.engineeringworldchannel.com/why-do-wind-turbines-fail). There are about 200,000 wind turbines around the world, and 117 fires take place annually. Blade failure was the most common accident, followed by fire, gear boxes, and structural failure. New blades with a 300-foot diameter cost about $100k per blade.

Solar panels have caused death and injury from home installers falling from a roof or by electrocution. These solar fatalities are small compared to coal and natural gas fracking accidents but must be included, and especially when compared to the zero radiation deaths in nuclear power generation.

Wind Generators - Capacity Factor

The wind capacity factor is about double that of the solar capacity factor. A major influence could be that wind can occur 24 hours per day and solar has a limited daytime slot.

Vaclav Smil of the University of Manitoba reported that the European Union measured a wind generator capacity factor of 21% from 2003-2007. The data were from wind generators in the North Sea that have different conditions than the American land-based wind generator sites. But the wind capacity factor is unfortunately somewhere between 20% and 40% of the total 100% time we desire.

Example 3-1. The Rim Rock wind farm in northern Montana uses 21,000 acres to install 126 wind turbines. Each turbine has a nameplate of 1.5 MW. The wind farm annual power delivered was 619 GWh. Calculate the capacity factor for the whole wind farm.

$$126\ x\ 1.5\ \ MW = 189\ MW\ Farm\ Nameplate$$

$$189\ MW\ x\ 8760\ \frac{h}{year} = 1.656\ \frac{GWh}{year}$$

$$\text{Capacity Factor} = \frac{619\ GWh}{1{,}656\ GWh} = 37.4\%$$

On average each Rim Rock wind turbine occupies 166.7 acres. What is the advantage to spacing wind turbines this widely? The advantage might be that since wind gusts are local, then each wind turbine can respond independent of it turbine neighbor, reducing the magnitude of the power ups and downs giving a more stable power.

The Electric Reliability Council of Texas (ERCOT) manages the flow of electric power to 90% of the state's power load [1]. The power load peeked at

ERCOT at 74,820 MW in 2019. ERCOT has 25 GW of nameplate wind generation and 3.6 GW of nameplate solar. Most wind generators exist on the panhandle and the northern border and Gulf Coast. ERCOT reports that the average capacity factor all these wind turbines in 26 counties is about 43%. This is large, Does it mean we are on our way to 100% renewables? No, there is no evidence of that. The intermittency is still there and requires a baseload backup. And the majority of Texas land does not have the wind of the western and northern regions. ERGOT is basically unregulated, and there was no grid back up when the cold weather power collapse happened in 2021.

Wind Power is an Old Technology

One of the ancient wind farms in Spain had heavy machines that show modern design features. These 12 windmills were an essential part of Miguel de Cervantes in his famous 17th-century novel Don Quixote. The Netherlands was an even earlier developer of wind energy to pump water.

Figure 5. Six of the 12 historic windmills of a 17^{th} century windfarm in Consuegra, Spain. A medieval castle is in the background. Each windmill was manually turned to face the wind. 70 pound bags of grain were poured from the top of the windmill into a grinding wheel below.

Conclusion

Nameplate power rating and capacity factor help us understand the variability and unpredictability of renewable energy resources. These two parameters show in numbers why renewables cannot achieve even close to 100%. Certain hydroelectric plants are the exception, but they are geographically limited needing good flowing rivers and dams. The current drought is the US southwest is lowering the Colorado River in Lake Hoover and Lake Mead that feed Hoover Dam and the Glen Canyon Dam. These parameters are important evaluation tools to critically evaluate political proposals that our society should get rid of coal, gas, and nuclear baseload generators and go all out for 100% renewables.

The issue of using renewables to achieve 100% renewable power delivery is still alive in the state of California (Los Angeles Times, August 18, 2020). At a California grid operator's board meeting, the issue was the recent power outage.

> "… Mr. Berberich faulted the commission for failing to ensure adequate power capacity on hot summer evenings, when electricity from the state's growing fleet of rooftop solar farms rapidly drops to zero but demand for air conditioning remains high. It's a challenge that will only intensify as California adds more solar panels and wind turbines to meet its targets of 60% renewable electricity by 2030 and 100% emission-free power by 2045."

Our data show that can't happen or even come close.

We know from the obvious truths that the sun doesn't shine at night or on rainy or cloudy days, and that wind is intermittent. We must rid ourselves of a baseload energy selection that is dominantly supplied now by coal and natural gas. We require dependable 24/7 electrical energy, as demonstrated vividly by the impact of the recent electrical outages in California. The Sierra Club 100% renewable energy promotion is a distraction from dealing sensibly with the fossil fuel baseload options facing us. Current nuclear reactors have virtually no emissions and have not had a fatality in the US in over 65-years of use in military and commercial reactors.

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Chapter 4

Hydroelectric Dams

All renewables have peak conditions that allow them to temporarily achieve nameplate power. But when all conditions are right, nothing matches the ability of hydroelectric to dependably power millions of people for extended periods. While hydroelectric power has weaknesses that are addressed in this chapter, hydroelectric power remains among its renewable competitors as the King of Renewables. The Grand Coulee Dam in Washington State, the Hoover Dam in Nevada, and the Niagara River in upper New York State have fed electricity the year around to millions of people for many decades. That is not the norm, but it happens, and it requires good water conditions. But a recent 20-year snow draught in the Rocky Mountains is threatening hydroelectric power capability in the Colorado, Columbia, and Snake Rivers.

We will first look at the dams that have generated immense power for over 70 years. And then address the weaknesses of hydroelectric power and close with an assessment. Hydroelectric power is not practical in most states, but it must be discussed because it has significant renewable contributions in other states. The United States has about 80,000 dams of which only 2,400 produce power (3 %). Most dams are used for flood control and irrigation.

Hydroelectric dams are easy to visualize. Gravity forces water to fall sometimes hundreds of feet and before striking the blades of a turbine that generates electricity. The higher the reservoir level, the greater the kinetic energy when the water strikes the blades below of a hydroelectric generator. There are also a significant number of dams that have no reservoir that get their waterpower from flow of water not the gravity. These dam designs of hydroelectricity are called Run of the River dams (ROR). The Ohio River has four ROR dams, and the Mississippi River is installing two. They have lower power in the tens of MW and have a seasonal dependance on spring runoff water.

A typical dam has a reservoir to store water that is carefully conserved. The hydroelectric dams of five major rivers are described to see the benefits, limitations, and risks. The Columbia, Snake, Colorado, Tennessee, and Niagara Rivers are distributed around the US, but the northwest region is hydroelectric dominant. These rivers use careful reservoir management to supply emission free electricity the year around. Less fortunate dams may shut down for the winter awaiting snow runoff in the spring.

The Colombia River starts at Lake Colombia high in the snow covered Rocky Mountains in the British Columbia Province of Canada. The river travels north of the lake for 150 miles before making a U-turn to the left and heading back to Washington and Oregon and ending 1,243 miles later in the Pacific Ocean in Astoria, Oregon. It is the second largest river in North America behind the Mississippi River, and most Americans east of the Rockies probably couldn’t identify it on a map. The Columbia River has 14 hydroelectric dams in its main stem. Eleven are in the US, and three are in Canada. The Colombia River supplies 44% of the hydro power in the US. There are 60 significant tributaries that support 400 dams, of which 274 dams are hydroelectric. The dominant source of Columbia water is snow melt runoff from the Rocky Mountains in Canada and the US.

The Grand Coulee Dam lies about midway along the length of the Colombia River. It is the largest hydro power generator in the US. Figure 1 shows its large reservoir driving the generators. The water that you see falling over the dam is not the water that drives the turbines. There are out-of-sight large pipes called penstocks that run water from the reservoir under the dam to the generators and river below.

The Snake River is a major tributary feeding a volume that is half that of the Columbia volume into the Colombia River at Pasco, Washington. The Snake River is 1,450 miles long and supports 17 hydroelectric dams. It originates and is fed by snow runoff from the Rocky Mountains in Wyoming.

(usbr.gov)

Figure 1. The Grand Coulee Dam in Washington state, The deep canyon reservoir is part of the Columbia River. The dam has a water height of 380 feet, a nameplate of 6.809 GW, a capacity factor of 36% and a yearly output of 20.24 TWh.

Further south, the Colorado River starts in the Rocky Mountains of northern Colorado running 1400 miles to the Mexican Gulf of California. It has 15 hydroelectric dams in the main flow. The Hoover Dam is the most famous and construction began in the 1920s. It powers Las Vegas and Los Angeles with a nameplate of 2.08 GW and a capacity factor of 23%. The dam suffered 112 deaths of workers in construction. The 4.717 GW Glen Canyon dam lies about 300 miles upstream. Its power output is more than twice the Hoover Dam.

March 22, 2022

The water level on Lake Powell is 100 feet from its high mark in August 2013. The dropping water levels are indicated by white marks on the canyon wall, often likened to a bathtub ring. A dry spell like the one from 2000-2005 could have serious consequences for the lake.

Figure 2. Lake Powell water level decline (Mark Henle / The Arizona Republic.

Lake Mead powers the Hoover Dam, and Lake Powell powers the Glen Canyon dam. The Colorado River feeds both reservoirs. The issue is declining water. Figure 2 shows the recent Lake Powell decline in water level. The water head is the difference in height between the reservoir and the generators at the bottom of the penstock tube. The power generated depends on the water head. If the head decreases 20 % then the power generated decrease by about 20%. A rule of thumb is that the output power decreases by just under 6 MW for every foot the reservoir level decreases. The river depends on spring runoff from snow in the Rocky Mountains. Winter snow droughts in the Rocky Mountains seriously affect dams on the Colorado River.

The southwest US water draught began about the year 2000 and today is a serious source of declining power production. As the hydraulic water heard declines so does the dam power output. The dams are now running at about 37% of full capacity. The terms crash point and dead pool estimate the water reductions where the level is below that necessary to generate power and the lower level where reservoirs stop feeding water downstream. The hydroelectric generation goes to zero when the level of water equal or is below the input penstock pipes. Water evaporation in the hot dry region is estimated to remove about 10% of its volume per year. The Glenn Canyon Dam is under serious consideration for entire removal. The Columbia River also is affected by the more than 20-year draught, but presently not as badly as the Colorado Rive reservoirs.

In the South, the Tennessee Valley Authority (TVA) controls a mix of electricity generators in the Tennessee River. The river originates just north of Knoxville, meanders 652 miles through Tennessee, Alabama, back through Tennessee, and feeds in the Ohio River in Kentucky. It is a tributary of the Ohio River. The TVA manages 24 hydroelectric dams, 3 nuclear plants, and 17 fossil fuel plants. The TVA was part of the1933 public works program.

In the East, the Niagara River generates a hydro plant nameplate of 2.68 GW. It is the oldest hydroelectric river in the US. In 1881 an immigrant from Germany Jacob Schoellkopf owned the Niagara Falls Hydraulic Power & Manufacturing Company, which by 1882 was the first company to generate electricity from Niagara Falls. The new Robert Moses power station was constructed about 4 miles below the Falls in 1957 to replace the aging, damaged Schoellkopf Niagara Power Station. The total power generation for the US and Canada is 4.9 GW. This productive side of hydroelectric generation will now turn to look at more serious weaknesses.

Horrific Dam Accidents.

Dams have a bad history of rupturing and causing instant down river flooding, death, and destruction. China's Banqiao Dam collapsed in 1975 killing 200,000 persons and destroying 62 down river dams (Figure 3). The Banqiao dam was built in the early 1950s designed by civil engineers who grossly miscalculated the structural challenge of such a large dam. (mveci48.wixsite.com)

Figure 3. The Banqiao Dam after the collapse. The exposed shoreline in upper part of scene gives a feel for the total release of water.

On August 17, 2009, the large 6 GW Russian hydroelectric Sayano-Shushenskaya Dam in Siberia suffered a major accident when one of its ten generators jammed (Figure 4). Two violent explosions then destroyed adjacent generators. The 1,500 ton turbine-2 was blown through the roof and 50 feet into the air. That precipitated the injection of 67,8000 gallons of penstock water per second into the room that crushed the other turbines. 75 workers were killed. Figures 4a and 4b show the dam on the Siberian Yenisei river before and after the disaster. The initial explosion knocked out the safety backup system designed to shut everything down in just such a catastrophe.

The cause of the accident was never nailed down, but clues exist. The warranty on the turbines was 30 years. On the day of the accident, Turbine-2 was 29 years and 10 months old. Strong vibrations and extraction of turbine foundation bolts preceded the explosion in Turbine-2. A root cause was senior management skimping on normal safety procedures. The dam had seemed so ideal with a 6 GW output, plentiful water flow, and no emissions.

(a)

(b)

(boston.com)

Figure 4a and 4b. The before and after pictures of this Siberian 6 GW dam.

The United States has not escaped these hydro power disasters. In 1887, Johnstown, Pennsylvania fell under an unusually large rainfall [1]. An upriver dam broke, and a flood of water 60 feet high traveling at 40 mph hit Johnstown killing 2209 people. The cause was inadequate engineering and planning of an upstream dam. Figure 5 shows damage on Mainstreet in Johnstown

Figure 5. Main Street in Johnstown after the flood had passed.
(commons.wikipedia.org)

Modern US dam accidents include the Teton Dam in 1976. The Teton Dam was an earthen dam on the Teton River in Idaho, United States. Eleven people died in an event that started with water leakage in the dam (Figure 6). The dam broke on the day that the Teton was being brought up for power for the first time. The damage was such that the dam after 4 years of construction and hundreds of millions of dollars was never repaired and brought online to deliver even 1-watt of power.

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Figure 6. Photos showing initial rush of flood water from the Teton Dam.
(Damfailures.org, en.wikipedia.org)

In May of 2020, two dams collapsed in the Tittabawassee River near Midland, Michigan (Figure 7). That quickly flooded the two towns of Edenville and Sanford. No one was killed when the upriver earthen dam at Edenville showed leakage just prior to collapse allowing evacuation.

Sanford Dam in Midland County breached. (photo by Martin Szeliga)

Figure 7. The collapse of the Sanford Dam on the Tittabawassee River in Michigan.

The Columbia River is a good examples of dam engineering in that the few accidents that happened never shut down the rivers. The Tennessee and Niagara Rivers have had serious spills. The evidence points to lack of adequate

66engineering knowledge and oversight when a dam is designed. Tight deadlines and cost can be compromised in a rush to get the job done.

The Columbia River has had two accidents among the 13 total dams. In 2014, a 65-foor crack was found in the Wanapum Dam. The river was diverted to the spillway during repair and the other dams continued to deliver power. In 2015, an explosion occurred in the generator section of the Priest Rapids Dam about 230 miles downstream from the Grand Coulee, and Priest Rapids was repaired without affecting the river flow to all dams.

Two other weaknesses of hydroelectric dams stand out. Dams take a large amount of land for the reservoir. Eminent Domain laws force people from their towns and villages. The other weakness is the restriction that a suitable nearby river exists. Of the 50 states in the US, only seven states have a hydro power contribution of more than 30%. It is said that dam locations in the US have maxed out. There may be space to cram another in but no more Grand Coulee scale dams. The 2,400 US hydroelectric dams have a capacity factor that ranges from 36.3% to 46.4%. Drought is a fourth enemy when the winter snowpack is thin.

The percent power contribution of dams has been mostly unchanged for many years. A challenge is to examine all dams for physical security. Sound engineering can make hydroelectric safe.

It is tempting to come down on hydroelectric dams based on the horrific accidents. But the Grand Collee Dam has been operating since 1942 without an accident. If you read descriptions of that dam, they often cite that more concrete was poured into it than any structure in North America. The Hoover Dam has over 400 feet of concrete at its base. That may support that bad engineering was responsible for many of the fatal hydroelectric dam accidents.

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Chapter 5

Limits of Renewable Energy

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The Goal of 100% Total Renewable Power

Iceland is a curious counter example of power generation on an isolated island. It gets virtually 100% of electricity from renewable sources. Iceland in 2018 generated 71% of its electricity from hydroelectric and about 29% from geothermal methods. Most of the geothermal energy also heats 85% of homes, buildings, sidewalks, parking lots, soccer fields, and swimming pools with direct piping of geothermal steam. Iceland consumes all of the electricity generated at a yearly per capita usage seven times that of Europe. Iceland has a small population of about 338,000 in 2018 and that reduces the challenge for renewables to supply a large population. The abundance of electricity encourages electrical use.

But Iceland has unique natural conditions. Iceland lies on the Mid-Atlantic Ocean ridge where the European and North American tectonic plates are pulling apart. This ridge forms the longest mountain range in the world creating a deep ocean spine of mountains running from the South Atlantic Ocean through Iceland. The ridge rises above the ocean in Iceland where one can walk in a narrow valley separating the plates. The tectonic plates generate hot molten rock beneath Iceland as well as earthquakes and volcanoes. There are 200 volcanoes and 600 hot springs in Iceland. There are many rivers and waterfalls, and an abundance of natural dam sites complete Iceland's good fortune. The high latitudes make solar energy weak and undependable with a yearly average of about 2.5 hours per day of solar power delivery. It has a population of about 350,000, so hats off to Iceland. It is an energy rich country.

In the U.S., a few states have achieved impressive renewable power share of total power from hydroelectric resources. These hydroelectric renewable power data are from the EIA reported in the New York Times on December 24, 2018.

- Washington. 71%
- Oregon 61%
- Idaho 61%
- Vermont 57%
- South Dakota 48%
- Montana 39%
- Maine 30%

On balance, these seven states have impressive renewable energy share, but that leaves 43 states with little to no hydro power. The river resource must flow the year around to be dependable, and in many cases the snow runoff water in the spring is good while not so good in the late fall and winter. The power generated by the hydroelectric dams must be backed up by an equivalent baseload generator to protect the expected power to customers when hydro is weakened or shutdown.

Costa Rica has generated 100% power for brief rainy-month periods. Around 2016, Costa Rica generated 100% of its power using hydroelectric (80.3%), geothermal (12.6%), wind (7.1%), and solar (0.01%). Heavy tropical rainfalls support five hydropower generating stations supplying 305.5 MW. Other contributing factors are a small country with a low population of 4.9 million people, a small area about half the size of Kentucky, and volcanos for geothermal energy. Costa Rica's tourism and agriculture are not energy intensive manufacturing industries, thus lowering the power demands.

Norway, Paraguay, Albania, and Uruguay approach 100% renewable energy delivery. These five countries have a common energy source and that is rivers and elevations for hydroelectric generation. Volcanos offer geothermal opportunity. Small regions of a large country can sometimes approach above 90%. Seattle is an example. Seattle uses seven hydroelectric dams to generate 88% of total power. 5% comes from nuclear for a fossil fuel free of 93% of its total energy. Wind contributes 4% (nameplate), coal, natural gas, and biogas contribute about 1% each.

Let's list some common requirements for approaching 100% renewable energies:

- Abundant rivers and dams for year around hydroelectric generation of more than 70%.
- Low population, less than about 5 million people to reduce power demand.
- Volcanos for geothermal electric generation and heat for buildings
- Wind is good, but currently contributes about 5% or less.
- Solar is not a major contributor at this point where good location and reliable year around generation is needed.
- Smaller regions such as states, counties, and cities within a country can be a location for high local renewable efficiency.

The Elephant Butte Dam on the Rio Grande in central New Mexico generates 28 MW of energy for eight months of the year. This unusual dam is turned off from mid-October to mid-February to store water in the Elephant Butte reservoir for spring and summer agriculture. The generators are turned on from February to October coinciding with snow runoff in the river from the Colorado Mountains and to support Rio Grande Valley agriculture irrigation. The electric generators are a secondary priority.

Professor Mark Jacobson and 26 co-authors from Stanford University proposed in a controversial paper a world using 100% renewable energy sources [1]. Several scientists pointed out weaknesses that included misleading assumptions of widespread hydroelectric dams using pumped hydro as a storage method and unrealistic assumptions in the ability of renewable energies to scale up to large populations [2]. Jacobson filed a $10 million-dollar defamation lawsuit that he later withdrew.

A Comparison of Two Country's Approach to Energy Source

Joshua Goldstein and Steffan Qvist compared two similar European countries and their approach to energy [3]. Sweden and Germany are industrialized countries located in northern Europe. In 1973, Sweden made a decision to reduce its dependence on fossil fuels having suffered through the 1973 oil crisis. They also wanted to clean the foul air from fossil fuel burning. The two countries took different paths with different results. We can learn from Sweden as it became the most successful country ever in reducing carbon electricity. France, Belgium, and Switzerland are taking a similar strategy.

Sweden has good hydroelectric resources, but it did not want to dam another river. Their strategy was to build four nuclear energy sites having a total of 12 reactors. Sweden now gets 40% of their electricity from nuclear power, and 40% from hydroelectric. Biofuels and wind contribute 20%. No fossil fuel is burned as Sweden merged nuclear and renewable energy sources and coined the word "nuables'. Sweden's decisions were not based on climate change considerations, although the results drastically reduced Sweden's greenhouse gas emission.

Each Swedish nuclear power site has a low quarter mile square footprint and delivers 24 terrawatt•hours of energy per year. The nuclear capacity factor is about 90%, and there have been no nuclear radiation accidents in over 35 years.

If that power generation had been done with coal, there would have been consequences. The daily delivery of 11 million tons of coal would require a coal train length of five miles per day and 1,800 miles per year. There would be 2 million tons of coal waste and about 700 Swedes per year dying premature deaths. Coal miner accidents and black lung disease would take more.

Germany reports a heavy investment in wind and solar energy sources that now contribute about 22% of the total power. Since the Fukushima tsunami damaged the nuclear facility in Japan, Germany has doubled its investment in solar and wind. At the same time Germany is decommissioning its nuclear plants in a response to Fukushima but is activating lignite dirty coal plants to make up the lost power. Coal increases CO_2 emission and nuclear plants reduce CO_2. This strategy puts energy sources in opposition that nullifies the gains in CO_2 emission from nuclear, solar, and wind.

The new German coal plants use strip-mined lignite coal that is the dirtiest of coal types. Lignite coal is now 25% of the total of 40% coal in the German consumption. Renewable sources are 29% and nuclear at this time is 13% and dropping. The premature death estimate from the new coal plants is 650 persons per year and 6,000 persons with serious lung disease [4].

Two downsides of the German investment in wind is that while 10% more renewable equipment was installed, the increase in generated electricity was only 1%. In 2017, the increased wind capability caused serious disruptions with full-on and full-off transients. This happened 100 times in 2017 putting strong electrical stress on the steady baseload generation.

Power Density Comparison of Renewables

All energy sources have a property called power density that is the amount of power that a generation source can deliver per unit area of its construction space. Power density is another parameter to compare energy sources and is typically measured in watts per meter squared (W/m^2). A higher energy source is desirable. Table 1 lists some energy sources and their power densities. The power delivered per square meter can vary depending on terrain area and capacity factors. Power density will be lower if a solar farm is placed in a hilly or a mountainous forest region than if placed in a relatively flat desert.

Table 1 Power Densities

Power Source	**Power Density W/m^2**	**Square Miles**	**Circle Diameter**
Nuclear	240.8	3.01	1.96
Wind	1.84	393.5	22.38
Solar	6.63	109.2	11.79
Hydroelectric	0.14	5,172	81.15
Biomass	0.08	9,050	107.3
Coal	135.1	5.36	2.61
Oil	194	2.1	1.86
Natural Gas	482.1	1.50	1.38

The power densities of the three fossil fuels are close to nuclear, but nuclear is markedly better than solar, wind, hydro, and biomass. We pay a heavy price for fossil fuel burning, but they are cheaper and have markedly better power density than renewables. Perhaps that is one reason why fossil fuels linger on and are difficult to replace.

These values are compared in Figure 1 where circle diameters are referenced to the output power of the 1.875 MW nuclear reactor plant at St. Lucie, Florida. Each circle represents the land area required for a power source to match the 1,875 MW nuclear plant. The circle radiuses are normalized to the nuclear area and calculated from Area $A = \pi r^2$. The St. Lucie plant has a power density of 409 W/m^2 and an area of 1.8 square miles. The area required by renewable energy sources to generate 1.875 GW is enormous. Nuclear plants have large capacity factors and emit no greenhouse gases or toxins. Figure 1 shows one of two major weaknesses for renewables. They require a large land area, and they are intermittent, inefficient, and undependable to power a large population. The calculation in Figure 1 used nameplate values for simplicity for the various power sources, indicating that the renewable energy areas are even larger.

<u>Question</u>: How can solar PV residential owners generate what is called positive net metering that delivers more power to the grid than used by a home or building? When this happens solar PV customers often get a rebate on their electric bills. How do they do this despite low-capacity factor conditions? Does this nullify the claims that solar can't power large populations with 100% renewables?

Whether net metering power during the day is fed into the grid or taken from the grid in a tug a war between the power demanded by the home and the solar power produced during daylight hours. When a house powers down as people go to work or to school, it is prime solar cell time for several hours, and the grid receives virtually all the solar power. If the resident solar panel is high wattage such as a 10 kW system, then net power can be loaded back onto the grid. But when the house power exceeds the solar power from the late afternoon until the next morning, the solar system needs the grid that provides power from coal, gas, or nuclear power.

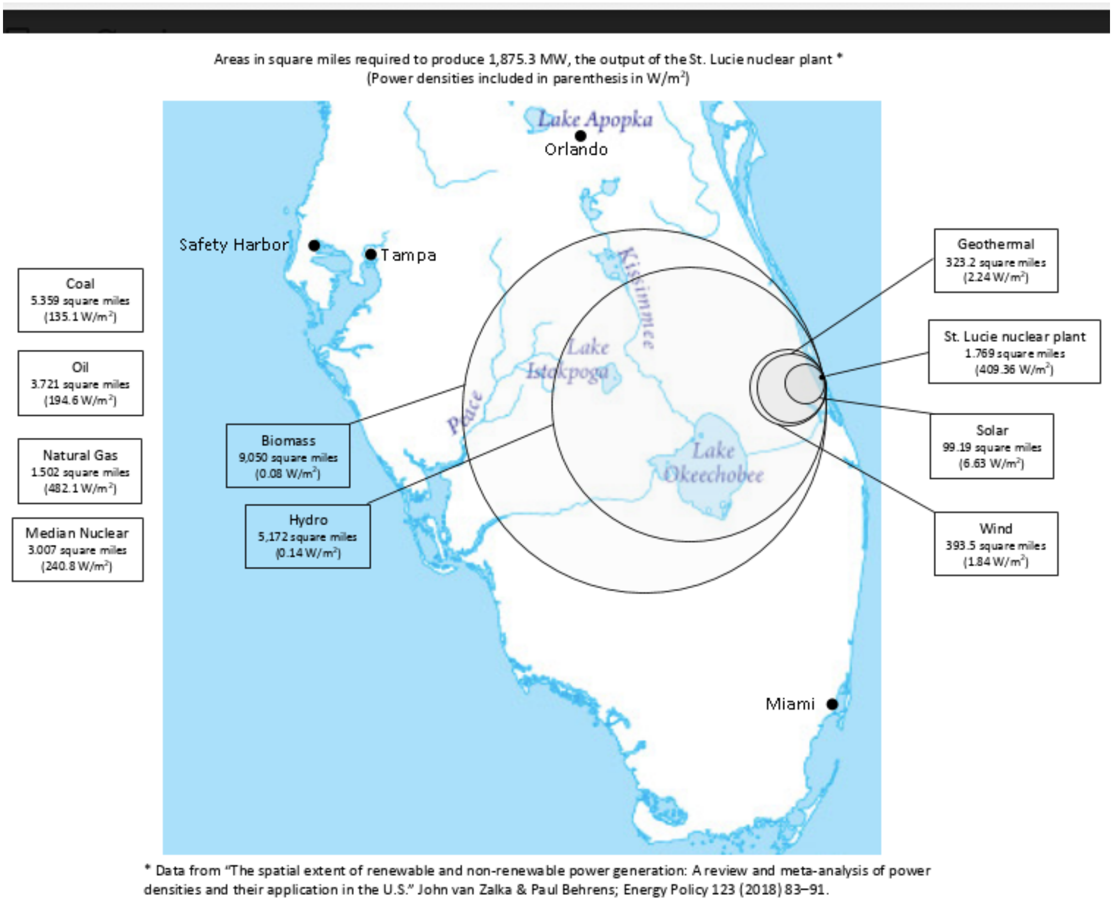

Figure 1. Power density of renewables. Fossil fuels and nuclear reactors referenced to the St. Lucie, Florida 1.875 GW nuclear power plant whose area is 1.769 square miles.

Data from the World Nuclear Association in the last row of Table 2 shows that the Albuquerque residential area has a net positive solar metering per day of 5.51 kWh injected into the grid while the US average drew 5.17 kWh from the grid. The higher the solar power nameplate rating, the better the chance of a positive net metering. A 10 kW solar system has a better chance of positive net metering than a 5 kW or a 2 kW residential system.

The stronger average solar power in the Albuquerque area (55.60 kWh) pumps more power into the grid than the lower US average (25.30 kWh) on a given solar day. The Albuquerque area average nameplate is 1.6 time stronger than the US average. These data indicate that most sites in the US don't have high enough solar power potential to achieve positive net metering. Therefore, they will draw energy from the grid that is dominantly powered by coal and natural gas fossil fuels.

Table 2. Residential Net Power Metering

Comparison of residential solar PV system factors

Factor	Albuquerque area residential solar PV system	Orlando area residential solar PV system	US average residential PV system
Average kW usage in residence	2.09	TBD	1.27
Average kWh/day usage in residence	50.09	TBD	30.47
kW rating of PV system (nameplate)	10	9.4	6.2
Average kW generated	2.32	1.555	1.054 *
Average kWh/day generated	55.60	37.32	25.30
Capacity factor (%)	23%	17%	10%-25%
Power density (W/m^2)	34	24	7.63
Residential average daily energy to or from grid	To (5.51 kWh)	From (TBD kWh)	From (5.17 kWh)

*A 17% capacity factor was used for the typical US residential PV systems as an estimate simply because it is about midrange in the 10%-25% range commonly stated in publications for residential and utility scale PV systems.

An important net metering point is that when the residential solar home is not drawing solar power, it must use the grid baseload power source such as coal or gas. It is overall good that when the net metering is positive, at that time there is less coal or gas consumed. The power company acts like an energy storage bank for the net power from solar.

Local adverse weather conditions on wind and solar renewables will drive the renewable numbers even lower. Nameplate values were used by the Sierra Club city 100% renewables proponents, and that gives a false estimate that should be at least 75% lower than the reported nameplate ratings.

Table 3 compares capacity factors and energy sources based on the percentage that each energy type produces output power. Nuclear markedly out-distances the other renewables with capacity factor numbers in the nineties, almost four times better than solar PV and almost three times better than wind. The EIA five-year average PV solar cell capacity factor from 2013 to 2017 is 26% indicating that the EIA PV data site had good weather and solar conditions for an optimum power measurement to reach 26%. If trees, bad weather, and shade from nearby buildings were factors, then we would expect the capacity factor to be lower, as low as 10%. This certainly affects the evaluation of energy sources in the aim for 100%.

Table 3. Annual capacity factors for non-fossil fuels. PV = photovoltaic, CSP = concentrated solar panel, MSW = Municipal Solid Waste, Conv. Hydro = Conventional Hydroelectricity.

Year	Non-fossil fuels							
	Nuclear	Conv. Hydro	Wind	Solar PV	Solar CSP	Landfill Gas and MSW	Other Biomass including Wood	Geothermal
2013	89.9%	38.9%	32.4%	NA	NA	68.9%	56.7%	73.6%
2014	91.7%	37.3%	34.0%	25.9%	19.8%	68.9%	58.9%	74.0%
2015	92.3%	35.8%	32.2%	25.8%	22.1%	68.7%	55.3%	74.3%
2016	92.3%	38.2%	34.5%	25.1%	22.2%	69.7%	55.6%	73.9%
2017	92.2%	45.2%	36.7%	27.0%	21.8%	70.9%	50.7%	76.4%

The EIA 5-year average wind generator capacity factor was 34% and conventional hydroelectric was 39%. Many hydroelectric dams shut down at night when electricity demands are low. This conserves the reservoir waterpower for daytime use. Some rivers deliver hydroelectric power continuously but unevenly such as the Columbia, Colorado, Tennessee, and Niagara Rivers.

Vaclav Smil of the University of Manitoba reported that the European Union measured a wind generator capacity factor of 21% from 2003-2007. The data were from wind generators in the North Sea that have different conditions than the American land-based wind generator sites. But the wind capacity factor is typically somewhere between 20% and 40% of the total 100% time we desire.

Energy Return on Investment (EROI)

There is another metric that compares the real cost of using these energy sources, which is the Energy Return on Investment. The EROI includes all energy sources in a system. It is defined as the ratio of the energy delivered by a power system to the amount of energy needed to drive that particular system. The higher the number the better the energy choice. EROI varies with time as components wear out or more efficient operations are developed.

$$EROI = \frac{Power\ delivered}{Sum\ of\ all\ costs\ to\ achieve\ power\ delivery}$$

The numerator is relatively easy since it is usually measured at the site. The denominator gets a bit detailed when we list all energy activities that enable or support the power delivered. The EROI estimate has boundaries. The EROI may be computed for just the physical site where energy is delivered, and money was ignored on further EROI data collection for other costs. Or it may expand the boundary to include the fuel delivery costs of truck purchase and maintenance, gasoline, and county road deterioration. Or it may expand to include the mineral mining and related activities. An even more inclusive boundary would expand to include health and fatality costs such as for coal power plants. All government subsidies must be included, and that is especially relevant for renewables.

Canadian tar sand drilling has a problem with the deep earth oil viscosity similar to cold molasses. This method injects steam down hole to liquify the oil for extraction. Making that steam and placing it down hole is energy intensive. It takes energy to create the output. This contributes to a low EROI of about 3 or less. https://insideclimatenews.org/news/20130219/oil-sands-mining-tar-sands-alberta-canada-energy-return-on-investment-eroi-natural-gas-in-situ-dilbit-bitumen

Oil and gas shale use the complex and expensive fracking technique that lowers their EROI. Ethanol made from corn needs the energy of farming that includes field preparation and care, fertilizer, farm equipment, labor, and transportation. Since ethanol reduces gas mileage for cars and other negative effects, its net contribution has long been suspected as a poor source of energy.

Table 4 shows the EROI for a variety of energy sources. Hydroelectric and nuclear stand out as more advantageous from an EROI view. The variation is due to the different design sizes among a particular energy source.

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Table 4. EROI Values for different energy sources.
(World Nuclear Association, Nov. 2017)

		Source	R3 energy ratio – EROI (output/input)
Hydro		Uchiyama 1996	50
		Held *et al* 1977	43
	NZ run of river	Weissbach 2013	50
	Quebec	Gagnon *et al* 2002	205
Nuclear (centrifuge enrichment)		See Table 1	81
	PWR/BWR	Kivisto 2000	59
	PWR	Weissbach 2013	75
	PWR	Inst. Policy Science 1977*	46
	BWR	Inst. Policy Science 1977*	43
	BWR	Uchiyama et al 1991*	47
Coal		Kivisto 2000	29
	black, underground	Weissbach 2013	29
	brown,open pit, US	Weissbach 2013	31
		Uchiyama 1996	17
		Uchiyama *et al* 1991*	16.8
	unscrubbed	Gagnon et al 2002	7
		Kivisto 2000	34
Natural gas	- piped	Kivisto 2000	26
	- CCGT	Weissbach 2013	28
	- piped 2000 km	Gagnon *et al* 2002	5
	LNG	Uchiyama *et al* 1991*	5.6
	LNG (57% capacity factor)	Uchiyama 1996	6
Solar		Held *et al* 1997	10.6
Solar thermal parabolic		Weissbach 2013	9.6
Solar PV	rooftop	Alsema 2003	12-10
	polycrystalline Si	Weissbach 2013	3.8
	amorphous Si	Weissbach 2013	2.1
	ground	Alsema 2003	7.5
	amorphous silicon	Kivisto 2000	3.7
Wind		Resource Research Inst.1983*	12
		Uchiyama 1996	6
	Enercon E-66	Weissbach 2013	16
		Kivisto 2000	34
		Gagnon *et al* 2002	80
		Aust Wind Energy Assn 2004	50
		Nalukowe *et al* 2006	20.24
		Vestas 2006	35.3

* In IAEA 1994, TecDoc 753.

EROI analysis provides a deeper look into the energy sources we invest in. A power company should do its own EROI to better understand what they are doing. We often see a solar panel or a wind generator farm and just see the solar panels or wind towers and nacelle generator and transmission lines exciting from the towers. It is rare that we see or consider the many related activities and their effect on overall cost and reliability.

But the decisions don't rest solely on the numbers. Coal has a good EROI for the boundaries that were used, but its toxic and greenhouse gas emissions make it a poor long-term choice. If the elimination of fossil fuel burning for electricity generation is a primary goal, then evaluating the total fossil fuel EROI medical expenses for premature deaths and minor fatalities. But nuclear and hydroelectric have significant EROI advantages to consider.

All renewable energy sources share the property of selective geography. such as solar needs sun and a shade avoidance site, wind needs consistent wind locations, and hydroelectric dams need a good river.

A final mention is that some utilities report that too much injection of power from renewable sites can overwhelm the grid making it unstable [4,5]. Hawaii and California have a large number of solar sites, One house in three in Hawaii has a rooftop solar system. A related phenomena is when the renewable inputs randomly inject a large fraction of the normal grid power sometimes reaching 50% and one report of 90%. When the plant has more power than the load demands, then it is said to go into a negative pricing. One solution is to pay large consumer customers to take the power. Germany, Texas, and California have reported this problem.

Conclusions

Renewables in these four chapters refute that solar, wind, biomass, and geothermal can solve our urgent need to eliminate toxic and greenhouse gases nor for safe and economic electricity generation. We must build upon a baseload source, and now we will compare our baseload energy options

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Chapter 6

Coal

Coal is the dirtiest, most lethal energy source we have

Michelle Nijhuis, National Geographic [1]

Juliette, Georgia is a small village about an hour drive south of Atlanta. Its charm is such that several movies were made there such as “Fried Green Tomatoes” with its famous Whistle Stop Cafe. A raw contrast is the Robert Scherer power plant located about three miles south of town with its four cooling towers and two huge nearly 1,000-foot smokestacks (Fig. 1). The Scherer is the largest single-point emitter of carbon dioxide (CO_2) in the United States [1]. Each day it devours coal from two to five 2-mile long coal trains. The Scherer emission pollution is estimated to annually cause 78 premature deaths, 110 heart attacks, and 1,300 asthma cases [http://www.catf.us].

The Robert Scherer coal comes by railroad from a large strip mine in Wyoming, and to impress us more, at any instant 36 coal trains are making the 3600-mile round trip to the Robert Scherer [1]. Coal trains vary in size, but a typical Wyoming Powder River Basin coal train may have 133 cars totaling around 19,000 tons or about 143 tons per car. Most coal cars are older, and the mechanical wearing of 143 tons on the rails, bearings, brakes, and bridges is unavoidable. Breakdowns are frequent and expected on this 10-day round trip. The travel is stop and go, and the average speed is about 15-25 MPH [2]. Objectively, there is room for improvement in coal fuel delivery.

Figure 1. Robert Scherer Power Plant emits 27 million tons of CO_2 per year. It has four units that can deliver a total nameplate power of 3.5 GW with a capacity factor of about 61%. [Photo courtesy of Georgia Power].

Wyoming coal cost was down to $11.09 per ton in 2009. A 135-car train at 110 tons per car would cost about $164,000 per trainload. Reports noted that the transportation cost outstripped the coal's value. These costs are significant when compared with other baseload generation methods. This coal transport system resembles a lethal Rube Goldberg design with fragile terrorist points at every river bridge, railroad rail, and at the plant. Scherer is a typical large-scale coal plant operation, but there is much more to learn about coal.

Overview

After about 125 years of energy dominance in the US, coal is now in a dive surrendering to cheaper natural gas [3]. Natural gas consumption passed coal in the US in 2017. In 2019, the Florida percentage of natural gas usage was 72% and coal was 12%. This brings radical changes that affect the livelihoods of communities and regions. The coal process includes mining, railroad transportation, pulverizing and burning the coal, toxic and CO_2 emissions, and coal ash waste processing. A proposal is that when coal is phased out in the US, it will be replaced with natural gas and supplemented with renewable sources such as wind, solar, geothermal, hydroelectric, and biofuels. This may happen, but we will describe serious issues that weaken this plan.

Price competition from natural gas and clean air regulations of toxic and greenhouse gas emissions are closing many coal plants in the US. In 2015, 94 coal-fired power plants closed, and more are targeted. Richard Martin predicted that by 2020 about 300 coal plant units of 1,300 total units will have closed [3]. [https://morningconsult.com/2016/05/03/coal-plants-shutting-without-clean-power-plan/].

The Eastern US coal business is also losing to the western Wyoming Powder River Basin where strip mined coal is cheaper. Western coal has more energy per pound that means a reduction in the number of coal chunks to get the same amount of electrical power. And natural gas is now cheaper than coal. The coal mining community is hurting, especially in in the Appalachian Mountain regions of Kentucky, West Virginia, Tennessee, and Pennsylvania. Six thousand coal miners lost their jobs in 2013-2014. Mining automation has also taken a toll on jobs. Each coal plant employs about 170 workers, and a modern replacement gas plant employs about 35 workers.

Coal miners powered America for so many years giving us the wondrous electrical based standard of living. In return, the miners suffered premature death and painful sicknesses such as black lung disease. The EPA (Environmental Protection Agency) is correct to regulate the coal emissions that kill and sicken so many of us. But the coal miners and families should not just be dumped. They should be supported to transition to other livelihoods. That is not easy, but we owe them. Coal's decline also hits the railroad freight industry, which previously took about 40% of its business from coal transport.

But coal will be with us for many years. China, India, Japan, and Germany are increasing coal burning as the most economical way to drive their manufacturing industry. These countries are aware of the many negatives of coal but give priority to their economies. Germany pushes wind and solar renewable energy more than any other country, but their rush to decommission nuclear reactors and replace their power generation with dirty lignite coal is disturbing. It is important that we understand the issues and human behavior! Coal is the river bottom feeder among energy sources. Let us look at the history of coal burning, and its severe negative consequences.

Coal History and Pollution

England was the first country to fully exploit coal, and England's long coal history is similar to the shorter US experience. England moved from a wood-based energy source to coal in the 1500s about the time that the English forests were severely depleted from over harvesting. The subsequent industrial revolution drove coal burning to painful excess [4].

England's early manufacturing cities such as Manchester and Birmingham choked on coal emissions that killed and sickened tens of thousands of persons per year [5]. Fatalities and death rates were accepted penalties, especially for the miners and the poor working class. Families could spend 12 hours underground with children given jobs where a small person could crawl. Richard Rhodes is an excellent resource on the history of English coal mining and subsequent development of the steam engine to support the coal mining industry [5].

Eventually the English mines were depleted of easily accessible coal, so today England has increased its natural gas, nuclear, and renewable energies, mostly North Sea wind. Their plan is to eliminate all coal plants by the year 2025 [6]. Now England must choose what technology will replace coal's electricity –gas, oil, nuclear, renewables, or combinations of these.

The US is following a delayed but similar track. The US transitioned from wood to coal in the 1890s. When Eastern US coal burning boomed in the early 20th Century, many cities like Pittsburgh and Philadelphia suffered severe health problems from air pollution. Devra Davis is an excellent resource [7]. What else to consider when phasing out coal? Let us look.

Coal Smoke Pollution and Scrubbers

Coal smoke contains more than 65 chemicals, including arsenic, lead, mercury, uranium, thorium, methane, cadmium, sulfur dioxide, nitrous compounds, carbon dioxide, and carbon monoxide. We inhale those toxic chemicals, and so do the vegetation and animals that we eat [7].

Sulfur combines with oxygen during the coal burn to form sulfur dioxide SO_2. SO_2 then rises in the atmosphere and combines with water in a complex reaction in the atmosphere to form sulfuric acid. This becomes acid rain that kills fish in distant lakes and rivers and wipes out forest regions. It also weakens healthy lungs. Nitrous oxide compounds (NO_X) cause ground level ozone, acid rain, and smog that can burn lung tissue, exacerbate asthma, and make people more susceptible to chronic respiratory diseases. Bad stuff. We like high concentrations of ozone at the upper atmospheric levels to block the harmful sun radiation, but we want zero or very low concentrations at ground level where we breathe.

Coal emissions pollute oceans, rivers, and lakes with mercury. Mercury enters the animal food chain and attacks the human nervous system. We eat fish that take up mercury causing a human nerve condition called mercury poisoning. A friend caught mercury poisoning by eating too much fish as many do considering fish to be a health medicine. In the northern Minnesota region where the Mississippi River originates in pristine forests and lakes, residents were advised to not eat their state fish, the walleye, more than once per week. Mercury pollution falls out of the sky with raindrops, and we find it everywhere.

Smokestack *scrubbers* were regulated in the early 1970s as a solution to capture sulfur, nitrogen, and mercury compounds (Fig. 2). These three elements are a limited subset of the total pollutants. There are about a dozen varieties of scrubbers. Although expensive and limited, scrubbers may be better than not using scrubbers. But are scrubbers the answer to coal pollution? Individual scrubbers don't address all pollutants, and scrubbers do not achieve 100% target pollutant removal. Scrubbers remove 70% - 95% of SO_2 compounds. Scrubber efficiency is a function of the type of coal, and the particular method to screen the pollutants. Duke Energy reported that a scrubber drew a huge 35 MW of power from its main power plant, and scrubbers can cost from \$500M to \$1B. There are better solutions.

Figure 2. An SO_2 scrubber for the Cardinal Plant on the Ohio River (American Electric Corp.).

Coal pollution has a legal friend. Many US coal plants do not have scrubbers and may never. A grandfather loophole in the law does not require coal plants built before 1972 to use scrubbers. By 2008, only 60% of the total coal plants in the US had scrubbers. Scrubber cost has driven many companies to keep old coal plants to the detriment of the population. The Environmental Protection Agency (EPA) addressed this air pollution problem, but controlling emissions raises the price of coal power plants. But what is the total cost if we don't fix air pollution? These expensive giant scrubbers are a clumsy way to deal with toxic pollutants especially when competing baseload generators either don't have the emission problem or at least have a reduced form. Scrubbers are like putting a body cast on a skin cut. There are better ways.

The Effect of Fossil Fuel Emission on Climate

We are stumbling down a bigger path. World greenhouse gas emissions are in giga tons per year, and a typical 1-giga watt (1 GW) coal plant emits about six million tons of CO_2 per year. One proposed cure is to capture the CO_2 and store it underground under high pressure in empty basins. This carbon capture has challenges such as transporting the gas emissions to a distant site, finding enough basins to store the enormous CO_2 volume, concern over leakage of the downhole pressurized exhaust gas, and the lethal effects when CO_2 surfaces in large, concentrated volumes.

The effect of atmospheric CO_2 concentration on atmospheric temperature has been demonstrated such as the genius technique that measures CO_2, methane, and temperature in ice cores drilled up to 2-miles deep in Antarctica, Greenland, and the Equatorial Mountains of Africa [8]. Each segment of the ice core represents a winter deposit of snow that can definitively measure ice depth as far back as 750 thousand years. With each winter, snow is deposited on top of the previous winter's layer, so an annual distinguishable layering occurs. And after 200 years, the top layers of snow compress the yearly material into an ice layer with small air bubbles inside containing ancient air samples.

Each year the ice core leaves a chemical signature, so that the depth of the ice core slices correlates each historic year with its air chemistry of CO_2, methane concentrations, and temperature of a particular slice of the ice core. Each slice of the core has tiny air bubbles trapped in the ice from hundreds of thousands of years ago. Incredibly, the air bubbles still have the original CO_2 and methane concentrations, and micro chemical analysis of a core slice allows a continuous plot of CO_2 and methane concentrations for hundreds of thousands of years. Isotope analysis of each slice allows an additional measurement of the temperature at which the air bubbles were trapped. A correlation is seen between higher CO_2 concentration and higher temperature. John Cox is a good read on the 20-year struggle to perfect the instrumentation, and the difficulties in perfecting the drilling and slicing [8].

Greenhouse gases in the atmosphere (mainly CO_2 and methane) correlate over hundreds of thousands of years with average global temperature. Water is a dominant greenhouse gas, but its life in the atmosphere is short. The temperature driven overall increase in atmospheric water contributes to extreme weather conditions.

The CO_2 and temperature curves go up and down together with a time lag of about 400 years. This phase lag in the Antarctic ice cores differs from that in Greenland, and the scientific observation is that the Ocean stores and releases CO_2 with a delay. The ocean acts similar to a giant electronic capacitor storing and releasing CO_2 with a temperature phase lag similar to that of voltage-current phase in resistors, capacitors, and inductors. The analogy compares the phase difference between a driving force of atmospheric CO_2 and a resulting current or in this case temperature.

Melting polar sea ice, melting glaciers, rising sea levels, and more frequent really extreme weather are some of the predicted manifestations of global climate change. As the sea level temperature rises, the water expands contributing to sea level rise. To whom do we send the bill? China, India, and other developing country's claim that those who caused the pollution should pay for it. This would target England, Germany, France, and the US who don't seem eager to pony up for their centuries of free pollution dumping to the atmosphere. But that does not get any country off the hook.

Death Rates

Coal mining and burning are lethal. Coal related death estimates do not give a precise number, but we can distinguish if yearly death rates are small (1 - 10), medium (10 - 100), or large (100 - millions). Total US miner fatalities in the 20th Century were estimated at 100,000 deaths. Current mine fatality rates are down to about 30 per year, while black lung death disease causes 1,400 premature deaths per year. Black lung disease occurs in miners who deeply breathe coal dust that can neither be destroyed nor removed by the body [4].

Estimates of the US general population premature death rate from breathing polluted air come from more than three credible sources. In 2000, Harvard University and the Massachusetts General Hospital in Boston released a study called the Six Cities that tracked populations in six midwestern cities over a 19-year period. Air pollution monitors were set up in the six cities, and 8,000 persons were interviewed for smoking, diet, exercise, and family history. The study showed that persons in the most polluted air of Steubenville, Ohio had a 26% higher death rate than those living in the cleanest air of Portage, Wisconsin. Coal emissions kill slowly and sicken persons in large statistical numbers. The study estimated 30,000 yearly premature deaths in the US due to coal plant emissions [9].

In 2012 the US National Academy of Science, Engineering, and Medicine released a report with an estimate of 10,000 annual deaths attributed to coal plant emissions. Both sides stand firm on their work. The EPA estimated 52,000 premature deaths due to *all* air pollution in 2005. Other studies estimate coal emission death numbers typically between 10,000 and 30,000. We won't repeat these numbers, but shouldn't public reflexes jump at any of these large numbers and object to coal burning? Shouldn't medical and death costs be added to the coal properties? The British Medical Journal, The Lancet, estimated that 1.2 million Chinese die prematurely each year from coal air pollution. Figure 3 shows modern air pollution in Beijing. Chinese miner premature death rate estimate is at 6,000 per year.

A recent epidemiology study on total air pollution was published in 2020 from the Harvard School of Public Health. That report estimated 60,000 premature air pollution deaths per year in the United States, and the World Health Organization (WHO) estimates 7 million worldwide. By any standard, these numbers are huge.

These coal fatalities dwarf the 2,996 fatalities of the New York Twin Towers attack in September of 2001; the 1,500 killed in the 1912 Titanic sinking, or the total of 4,486 U.S. soldiers who were killed in Iraq between 2003 and 2012. But the public generally doesn't complain about coal because the deaths are delayed and seemingly unconnected to the source. Delayed death is commonly thought of as bad luck. Why does coal get a free ride? Consider the public convulsions if gas or nuclear reactors were close to these lethal numbers. The gas industry reports drill site fatalities that are in the hundreds per year. Nuclear data report *zero radiation deaths* in the US since the first power plant over 65 years ago. Are we nuts?

Figure 3. Coal and auto emission air pollution in Beijing, China air pollution is a modern version of the 1952 London air pollution. That is not fog. (Global Sherpa, by Jason Walters, January 14, 2013)

Killer Smog

Historically, killer smog descended when high pressure warm-cool air inversions occurred, and pollutants became trapped in the cool air at the ground level. There have been dramatic instances of coal pollutants and inversion temperatures that create intense deadly smog conditions [5,7]. A five-day cold air inversion in London in December 1952 took 4,000 lives in five weeks when air visibility was sometimes less than a foot (Fig. 4). A similar incident occurred in the small Pennsylvania town of Donora in October 1948 when air pollutants killed 70 persons within two weeks of a cool air inversion [5,7]. The coal history of Europe and China reports many such killer smog events due to polluted air.

Figure 4. London air pollution on December of 1952 due to a weather cold air inversion and abundance of coal exhausts from homes, factories, and coal power generators. That is not fog. (Sage Magazine, by Gabriel Isaason, February 2012)

More on Coal Transportation

Transporting millions of tons of coal per day across the country is an enormous waste of energy (Fig. 5). About 40% of the coal used in the United States comes from 18 mines in the Powder River Basin spread over Wyoming and Montana. Jeff Goodell reports that about 110 coal trains per day leave the Wyoming Powder River Basin [2]. The process is described as a continuous national conveyor belt.

Figure 5. Coal trains in Danville, West Virginia moving out across the country. The constant travel of old, heavy coal cars causes frequent reliability failures. (Mother Jones, March 12, 2010)

Coal train accidents are frequent. For example, in July 2012, five coal trains derailed causing extensive equipment and rail damage, and transportation delay. Two persons were killed in Chicago in this epidemic of crashes. Aging heavy railroad equipment, rails, bridges, coal dust, and bad weather make safe transportation difficult.

Other coal train wrecks have occurred near coal export stations on the Pacific Northwest coast. In July 2012, a 31-car wreck occurred near the Columbia River Gorge in Pasco, Washington spilling six million pounds of coal. The coal was moving from the Wyoming Powder River Basin to a coal export terminal in British Columbia. Plans are for six more west coast coal export terminals that would add about 30 coal trains per day through the region.

Coal distributors moved coal via rail, barge, and truck. But rail was the dominant mode of coal transport, accounting for almost 70 percent of the domestic coal shipped during 2008. About 20% of US coal delivery is by barge to the Midwest using the Mississippi and Ohio Rivers. Indiana, Illinois and Iowa get coal this way, and Florida gets some coal by barge from the Mississippi River.

Coal dust is a result of grinding coal into a powdered form. It accumulates in coal freight cars, underground mines, coal power plants that pulverize coal into powder, and near the rails of coal freight trains (Fig. 6). It has been listed as a cause of derailment [10]. It leaves a dirt black film. Washington Department of Health reported that coal dust contains lead, mercury, and arsenic. It also contains soot and black carbon that is the stuff of black lung disease.

Figure 6. Coal dust given off by a coal train. (Sightline Institute)

Coal Dust: The Burlington Northern and Santa Fe Railroad (BNSF) stated that, "*BNSF has determined that coal dust poses a serious threat to the stability of the track structure and thus to the operational integrity of our lines in the Powder River Basin."* You probably don't notice coal dust if you live further away from their sources.

Coal Ash Waste

Coal deposits an ugly amount of waste called slag. Some waste goes up the smokestack as fly ash, and larger chunks fall to the bottom of the boiler. 130 tons of coal ash was generated in the US in 2014. The waste contains arsenic, mercury, lead, radium, uranium, and many other elements. The amount of waste varies with the type of coal, but 10% of initial coal weight is a good waste estimate. Fly ash is fine, powdery silica. Bottom boiler waste is in a molten state, and it is removed by opening a large plug at the boiler base

Storing coal slag is a problem. It is often placed in a pond and is especially dangerous when large slag piles in liquid form accidently dump into a river. Kingston, Tennessee and Eden, North Carolina are recent disaster sites. In 2008, the Kingston plant accidently dumped 1.2 billion gallons of ash into the Clinch River. The mudflow spill covered 12 houses. In 2014 Duke Energy reported that the Eden plant dumped 83,000 tons of ash and a 27-million-gallon dump of that ash into the Dan River. About 7,200 pounds of arsenic entered the river.

Coal ash has a deadly history. The heavy coal slag waste at the bottom of the boiler is removed by opening a plug at the bottom of the boiler draining the molten waste into a large cooling tank called a slag tank that contains water. The molten waste can reach 1,000 ^{O}F. Water cools the molten ash, and it forms a glassy material. A drain plug malfunctioned at the Tampa Electric Company (TECO) in June 2017. The workers beneath the plug were suddenly drenched with material that resembled volcanic lava. Two workers died, and four others badly burned. A similar TECO accident occurred in June 1997 injuring and burning four workers (Tampa Bay Times, July 1, 2017).

Fortunately, slag tanks are being replaced with a design that safely retrieves the molten slag from the boiler. In 2015 there were still about 30 coal boilers with slag tanks. TECO estimates that it may cost up to $250,000 to shut down a boiler. It takes about 12 hours to bring one up. Companies don’t like to shut down boilers for a couple of reasons. Power is not sold when boilers are down, and the reduced generating capacity might only be offset by purchasing power from another company.

About 43% of the annual 125 million tons of fly ash has commercial applications. The major uses are in concrete, soft soil and embankment stabilization, road sub base construction, and as filler in many construction materials.

Coal Life Expectancy

A mantra among some coal executives and many politicians is that the US has 250-300 years of coal based on our current use. This may be true if we include all the resource coal that lies deep beneath the surface rock. However, as with oil, there is a point of diminishing returns that involves unacceptable investment. Deeper coal seams create more difficult, dangerous, and expensive mining. There can be undesirable consequences of very deep coal mining. There is a financial stopping point.

The United States Geological Survey (USGS) studied the economic accessibility of coal in the Wyoming Powder River Basin and concluded that the typical surface mine has less than 20 years of reserve life. There will be coal remaining, but it will be found far below ground and be more expensive to mine. The US uses about one billion tons of coal per year and 40% of that comes from the Powder River Basin [2].

Strip mining

Strip mining is the cheapest coal mining, but it is tearing up sections of the US [2]. About 10% of the Appalachian Mountains in West Virginia have had their tops removed (Fig. 7). The mountaintop ground layer is dumped in the nearest valley polluting and impeding the residing streams. Coal is washed prior to shipping, and those waste pools can seep into the ground water.

Total Coal costs

Coal power generation is relatively cheap to the consumers, but coal power is not cheap when medical care, death rates, minor injury and fatality, pollutant sequestration, acid rain, and climate change expenses are added to the accounting. Coal emissions are dumped free of charge into the atmosphere. The increase in medical and death costs due to coal pollution are hard to estimate, but let's approximate a coal medical cost at \$0.05 – \$0.06 per kW·hour [7]. If that medical cost was only an extra \$0.032 per kW·hour, then costs of coal-based power would increase 50% and other energies would be competitive.

Figure 7. Mountain top removal for coal mining in the Appalachian Mountains of West Virginia. The WV Massey Energy Company, now Alpha Natural Resources, has been proactive in this practice. (From US Environmental Protection Agency)

The Freedom Industries Corp. of Charleston, WV supplied a foaming agent that separated crushed coal from soil and rock particles. In January 2014, a chemical leak occurred at this plant on the Elk River. The toxins got into the downstream in the nearby Charleston city water supply affecting 300,000 persons. The city essentially shut down until water levels could be verified as toxin free. Restaurants and home cooking shut down, baths and showers were stopped, and only toilet flushing was safe. People left town for a few days. Accidents happen, but coal has an unacceptable health risk, and this must be included in our comparative analysis of other energy sources.

Coal Emissions

Table 2 compares the coal emissions with natural gas. While natural gas emits considerable CO2, it is impressively clean compared to coal. Gas does have another weakness called fracking that we will detail in the next chapter. Lung disease is strongly tied to the coal pollutants. But the gas toxin reduction in coal is astounding.

TABLE 2. Gas-coal emissions

Pollutant	Natural Gas	Coal
Carbon Dioxide	117,000	208,000
Carbon Monoxide	40	208
Nitrogen Oxides	92	457
Sulfur Dioxide	0.6	2,591
Particulates	7	2,744
Mercury	0	0.016

The British government calls for closing all coal-fired power plants by 2025 and proposed that the plants be restricted two years before that (BBC, November 2015). Few countries have adopted such a change. When coal is removed from the mix, the power deficit must be made up by other sources. What do you choose? The energy mix for the United Kingdom in 2015 shown in Table 1 shows 20.5 % coal that must be replaced by something. The British are counting on nuclear and renewables.

Table 1. British Energy Distribution in 2015.

UK electricity mix	
Energy source	%
Gas	30.2
Renewables	25.3
Nuclear	21.5
Coal	20.5

Summary

Coal's overriding asset is its deceptive low cost to consumers, and it has an established system that can generate mostly dependable electricity. But the negatives are huge surpassing any competitors. Fatalities, chronic sickness, greenhouse gas and toxin emissions, strip mining, scrubber cost and inefficiency, ash waste, and a wasteful energy transport system highlight the negatives. Michelle Nijhuis wrote in the April 2014 issue of National Geographic that, "Coal is the dirtiest, most lethal energy source we have" [1]. It might be called Killer Coal. This total package of deadly properties must be weighed against competing energy generation sources that have none or a fraction of coal's death rates, greenhouse emissions, and other severe negative factors.

There is recent activity by the US Environmental Protection Agency (EPA) to address air pollution. The battle lines are drawn with opponents of cleaner air claiming the country will suffer hundreds of thousands of lost jobs and the economy will be ruined. There is little recognition of the cost of air pollution or information that the lost job count is accurate. Coal is the worst of our energy options.

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Chapter 7

Natural Gas

"When debating these energy issues, one practice is to list the positive attributes of your choice and then the negative attributes of your opponent."

Richard Muller, physicist UCAL Berkeley, CA

There is electricity in the air, and it's about natural gas energy. The greatest revolution in energy may not be in renewable sources but in natural gas - or maybe not. When utilities replace coal electricity generation with gas, is it because gas emits half of the CO_2 of coal, or that gas does not emit the sickening toxins of coal, or that gas does not kill as many people as coal? No! It is because a new gas drilling method called *fracking* makes gas *cheaper* than coal. It is about cost as it has always been and always will be with the utility industry. Let's talk about the short past, the brief present, and the possible crashing wave of the natural gas future.

Overview

We can identify three education layers in fracking technology. The first is an easy description of drilling, frack explosions, gas and oil retrieval, waste fluid disposal, and transport of fuel to market, -very visual. A second layer examines the whole fracking operation in more detail. At this level you can make judgments on gas and fracking - push yourself to understand. The third layer of learning is where the engineers and technicians live, and that is mostly beyond the purpose of this book. Make no mistake. It is not simply drill, explode, retrieve, and send to market. There are necessary details to dig out, to understand why the economic life of each million-dollar well is about 4-5 years, and why the data show that the extensive natural gas reserves in the US may have only 20-30 years of production life and not hundreds of years. Let's begin the journey.

Large shale rock areas lie within the United States with gas and oil molecules trapped in the rock [1-9]. The molecules do not chemically bond to the rock, so the challenge over 50 years was to find a way to drill, and to free and retrieve these energy molecules from their rock micro-cages. That is what fracking does. We will overview fracking; what are good points and bad points.

If there was a fracking Hall of Fame, George P. Mitchell would be the first inducted. The history of gas fracking goes back over 50 years, but Mitchell brought it to economic fruition in 2001 after 17 years and spending $6 million to develop fracking in the Barnett Shale in Central Texas [1,2]. They were frustrating years, and he almost lost his company by funding the development. Large energy companies had tried and failed. He drilled several thousand feet to the shale rock, and then exploded the rock with a chemical solution under high pressure. It was not his idea, but he made it work. The fissures in the fractured rock extended hundreds of feet, and the released gas and oil molecules were collected at the well ground surface. A bet made on its success would have seemed like a bad bet, a really bad bet. But as a mathematician once said, low probability events happen.

Mitchell obtained a petroleum degree from Texas A&M, and his work shattered the world energy business from the Middle East to the US to Asia. He added an innovation that made fracking profitable, or commercial as energy folks refer to it. Modern drill heads can be driven in any direction. So, a vertical drilling down two miles is next directed horizontally to tunnel *within* a rich horizontal rock stratum for as long as a mile or two. This greatly enhanced the retrieval region and profits, and the fracking revolution was on. Imagine the end of the borehole three miles distant, where you are performing intricate operations at that distance.

Figure 1 shows a drill site under construction. The drill tower is visible as are several trucks and other equipment. When the drilling operation is complete, gas is delivered to a pipe that leads to a gathering station for several wells. All of this drilling equipment is gone and only a small gas gathering assembly is left.

Fracking was economic to an extent that horizontal fracked gas and fracked oil became cheaper than coal or nuclear power. Gas and oil prices dropped for consumers, and America's dependence on foreign energy got a reprieve. Gas and oil are both fracked using the same technology.

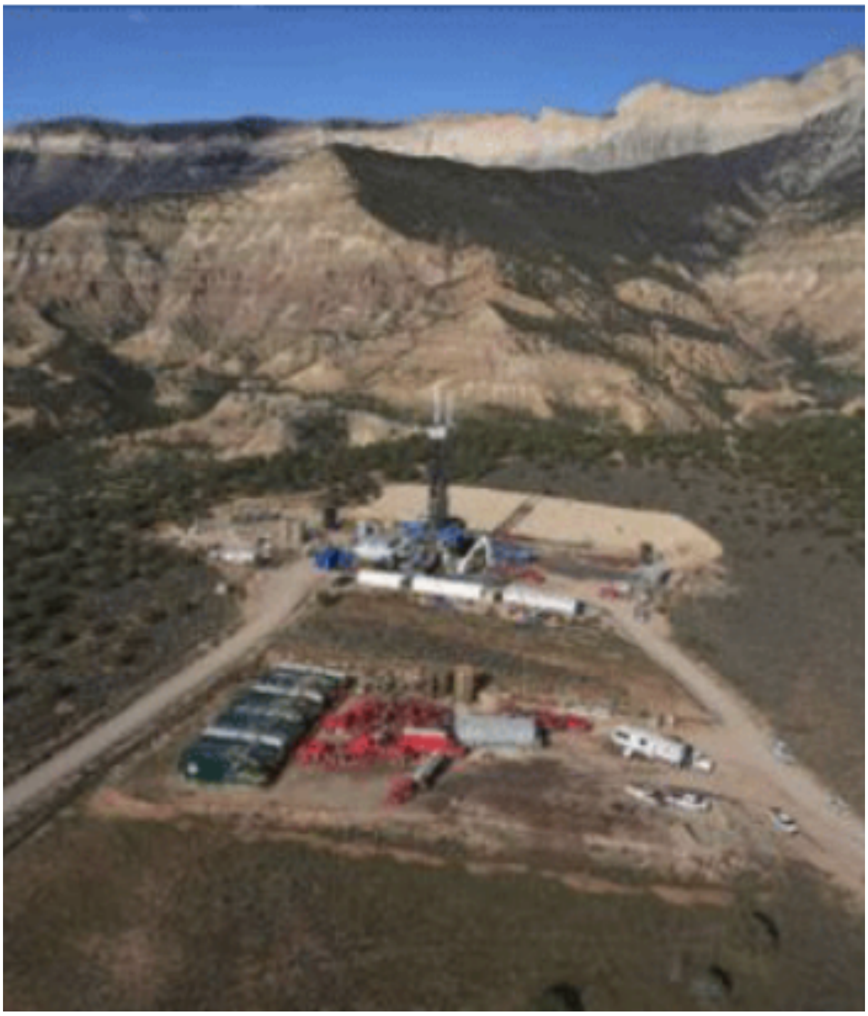

Figure 1. A frack drilling site under development. (Bureau of Land Management)

But maybe gas is not so great. Although methane emissions are basically free of the lethal toxins of coal, and CO_2 emission is half that of coal, there are other concerns. Those tiny CH_4 molecules of methane gas can easily wiggle and leak through small holes or cracks in the gas gathering equipment and transmission pipes. Gas leakage is significant, since CH_4 is about 86x more potent as a greenhouse gas than CO_2 when CH_4 atmospheric depletion is averaged over 20 years. Methane differs from CO_2 in that CH_4 may significantly last tens of years in the atmosphere while CO_2 lasts hundreds of years.

Other gas downsides include earthquakes linked to the fracking operations. The earthquakes are not linked to the fracking explosion itself but to the weight of underground storage in a basin with millions of gallons of used waste drilling fluid. A vulnerable junction of rocks can slip causing the earthquakes. In August 2016, a 5.6 Richter scale fracking related earthquake struck Oklahoma fracking country. The quake was felt as far as Chicago, St. Louis, Kansas City, and Phoenix.

Another irritant to local homes is that the initial drilling operation goes on 24/7 for 3-6 weeks depending on the rock properties and depth of the hole. It takes a tough individual to work the oil and gas fields. Crews work 24/7 to drill and capture the gas and oil in extreme weather conditions such as that found in Montana, North Dakota, Pennsylvania, Texas, Arkansas, and Oklahoma. Workers continually assemble and then disassemble the 50 ft. 600 lb. pipes in slippery rig decks, extreme hot, cold, and windy weather, when injuries and fatalities are serious numbers.

While rig jobs pay from $60k to $90k per year, these jobs will only last as long as wells are drilled. It is not a life career. Recent dips in the price of natural gas and oil have scaled back drilling new wells. There are other downsides to job creation. A new semi robot called an “iron roughneck” has appeared to mechanize the pipe assembly. Tasks that used to require 20 people are reported to need only five (https://www.youtube.com/watch?v=Gz-pATgoevQ). Let’s turn for a moment to what the future might be in this truly industry disruptive fracking technique.

Natural Gas, What and Where is it

It is exciting for modern gas and oil drillers to see the world in terms of the energy abundance opened up by the fracking operation in the United States. We might share their excitement and turn a blind eye, if as home and farm owners we became millionaires from a modern oil and gas drilling company. The money can be huge, and you can also line up as a patriot strengthening America's energy position in the world. But in this excitement, you cannot shrug off the downside. As a minimum, one should recognize and work on the problems as high reliability technologies do.

Figure 2 maps the shale gas and oil regions in the lower US. Virtually all the shales have some fracking activity. The industry refers to a shale region as a "play." At first glance the large shale areas on the map inspire hope that the US has enough gas (and oil) to last 100 years or more. Just look at the immense area of the shale fields.

The Barnett play in Central Texas is where modern fracking development began in the 1990s, and the Eagle Ford shale in lower Texas has been producing since about 2005. The Marcellus shale in the northeast has been under active drilling since about 2006. The Utica shale adjoins and goes underneath the Marcellus shale on the west, and together they are the largest gas shales in the country extending even into the Great Lakes [3]. The gas wells in the Utica shale may lie a mile beneath the Marcellus shale. The Williston Basin in North Dakota, Montana, and Canada has been active since about 2005. It is more known by the popular name of the Bakken shale. The Bakken play has gas, but it is dominantly oil.

Figure 2. A US map of major gas and oil shales. (Energy Information Agency (www.eia.doe.gov)

Natural gas that is pulled from the well is mostly methane, but it also has ethylene, propane, and butane that are later refined out for industrial use (Table 1). These latter three gases are called the Liquid Natural Gases, and they have commercial use in the petrochemical industry.

But the rapid depletion of a well, the small percentage of profitable shale area, the expense of maintaining non-profitable wells, and the extraction properties of shale gas trim these hopes. Wells typically reduce to 20% of initial flow within one year and 5% at five years. Population density, road and water access, rock hardness, and depth of drilling affect the cost of drilling. Texas and North Dakota have large areas with smaller population density and easier road access than the Marcellus in Pennsylvania. The issues are not as simple as reading a map.

How many wells are there? The US Energy Information Agency reported that between 2009 and 2014 the total US natural gas well count went from 493,100 to 514,786. The 2009 and 2011 Texas gas wells went from 93,507 to

98,279 and Pennsylvania went from 57,556 to 70,400. Baker-Hughes Inc. reports the weekly number of new oil and gas drillings called rig counts. Rig count is the growth parameter. Baker-Hughes natural gas data showed the US dropped from a rig count of 328 in 2014 to 162 in 2015. These approximate numbers change weekly. The fall in natural gas price is given as the reason. These are the normal ups and downs of the fracking industry.

The natural gas drawn from a well has other components. Table 1 show other gases that must be refined out. Some have a lower ignition temperature and that can cause accidental explosions.

TABLE 1 – NATURAL GAS SPECIFICATION (Energy Information Agency).
http://www.eia.gov/forecasts/capitalcost/pdf/updated_capcost.pdf

Component		Volume Percent
Methane	CH_4	**93.9**
Ethane	C_2H_6	**3.2**
Propane	C_3H_8	**0.7**
***n*-Butane**	C_4H_{10}	**0.4**
Carbon Dioxide	CO_2	**1.0**
Nitrogen	N_2	**0.8**
Total	--	**100.0**

Billions of dollars are being made and lost by gas and oil companies, and lesser amounts by property owners who signed off their mineral rights to mostly small, aggressive drilling companies [3]. Natural gas is now cheap, and many power utility companies are rapidly converting most of their coal generators to gas. If gas prices rise after these equipment investments, then we may be locked into an expensive energy source. We next describe the mining process, and then list the major pro arguments with rebuttals.

The Good, the Bad, and the Ugly

Gary Sernovitz is an unusual figure in the fracking revolution [1]. He is a Managing Director who directs energy investor relations and strategic development. His company fracks. He left his initial job as an oil-equity research analyst with Goldman-Sachs after three years to dedicate a six-year poverty life to writing novels. Then he returned to the oil and gas industry, and now combines a writer's wit with access to oil and gas industry data. His writing style is unique in that no other writer on these issues can combine knowledge and a sense of humor.

We will follow Sernovitz's train of thought. It begins with taking a view altered from a John Lennon song "What if there were no fracking". What if there were no gas and oil fracking? Sernovitz is conflicted as he writes that the US would not have rapidly experienced the following:

- A coal decline allowing an annual reduction in CO_2 emission of 556 million metric tons
- Energy independence from several countries some of which express dislike for America
- A more than 50% reduction in gasoline prices loosening money for the financially strapped public, and stimulating the economy
- A 40 percent rise in natural gas production in the United States and a 70 percent fall in natural gas prices
- A stronger dollar and reduction of the trade imbalance
- Political strengthening of the US with respect to Middle East countries. The Associated Press reported on April 26, 2016 that the six oil exporting countries in the Middle East suffered a $390 billion loss in 2015 and expect a loss of over half a trillion dollars in 2016. Fracking in the US along with OPEC pricing are major players in a low barrel price of oil.

Each bullet item above is huge, and to collect six in such a short time was not imaginable in the 2003-2010 era, but fracking and horizontal drilling of gas and oil did quickly change the energy world. There are counter views, some of which are

- The gas reduction in CO_2 emission is significant, since half is still large.
- Initial fracked gas and oil well production falls off rapidly to about 20% after one year and to 5% after 5-years.
- The rapid initial fuel falloff and small percentage of profitable shale area drilling raises questions of the long-term profits.
- The fracking of gas and oil may peak in a few years. Is fracking a temporary success?
- Methane CH_4 has a leakage problem throughout the entire production process of fracking and delivery. CH_4 is a more powerful greenhouse gas by a 25-86 factor depending on how many years you wait after emission of the CH_4 to evaluate its effect.
- In some regions (especially Pennsylvania), fracking is disruptive to the environment of homes, forests, country roads, clean air, animals and water, and to the health of humans.
- Rig worker fatalities and injury are serious numbers.
- The fracking process is responsible for significant increased earthquake activity near the drilling liquid waste disposal sites.
- There are serious financial challenges that caution that fracking may not sustain in a few short years.

I spent several years in the electronic integrated circuits (chips) industry doing testing, locating, and minimizing reliability failures. It was meticulous work practiced worldwide. And that was rocket science compared to the 5-7 fracking bullets above. Leaks, earthquakes, and worker death and injury are fixable. The first four bullet items are inherent and not fixable. Fixing the last four bullets is manageable, but it eats into profits when you spend large sums on them.

Fracking – Government and Private Teamwork

There is a strongly expressed feeling that the free enterprise system created the revolutionary fracking technique, and the government was only an impediment. Let's examine this statement. George Mitchell overcame challenges and human obstacles in his quest, but he stood on a technical base financed by the government from the 1980s. That included about 20 prior years of US Federal Government funded research for private companies, government labs, and universities [5,6]. Sandia National Lab contributed to seismic fracking analysis, computer applications, and the ability to display and remotely direct a drill head to oil or a gas laden shale layer. And significantly, only the federal government had the money to sustain financial support for 20 years in the early stages of fracking development.

Mitchell was generous in acknowledging his collaboration with the National Labs. Only the Federal Government had the resources and staying power to keep the research effort going when progress was slow. The federal government aided private efforts in several ways: basic science and resource mapping; coordinating and complementing industry efforts; applied research and development; and tax credits for unconventional gas. Jack Paulson describes the famous "Section 29 tax credit" in the Windfall Profits Tax Act of 1980 [6]. Gas companies were credited with $1.00 per mcf when wellhead price was $3.00 mcf. That was a huge tax stimulus for gas mining.

Michael Giberson listed the following federal contributions: [5]

- "Slick-water fracking, the technology that Mitchell used to crack the shale gas code, was adapted from massive hydraulic fracturing, a technology first demonstrated by the Energy Department in 1977."
- "Mitchell learned of shale's potential from the Eastern Gas Shales Project, a partnership begun in 1976 between the Energy Department's Morgantown West Virginia Energy Research Center and dozens of companies and universities."

- “Mitchell’s success depended on a revolution in monitoring and mapping technologies driven largely by government labs.”
- “Sandia National Labs provided Mitchell with many critical micro seismic tools.”
- “Mitchell also benefited from 3-D imaging, which the Energy Department had long supported.”
- “The third critical technology was horizontal drilling and well installation …. In 1976, two government engineers … patented an early-stage directional drilling technology that became the precursor to horizontal drilling.”
- “A joint venture between the Energy Department and industry drilled the first horizontal Devonian shale well located adjacent to the Marcellus shale.”

We can only praise Mitchell’s special achievement but must point out it was the collaborative power of the government and the private sector that made it happen. These points are brought up to counter the often heard cry in the industry that “if you want to move quickly, get the government the hell out of the way.”

“If you want to move fast, go it alone. If you want to go farther, go together”

-African Proverb

There are many other collaborative American government-private examples outside the gas and oil business that include production of the first commercial jet in 1958. The Boeing 707 was the fourth four engine jet airplane that evolved from over 13 years of development by military and Boeing funding. The first two predecessors were military bombers. The third four engine jet was the KC-135 airborne refueling aircraft, that was nearly identical to the subsequent 707. Passenger seats replaced large fuel tanks, but the bugs were long removed for the commercial aircraft. Recently the strong lightweight composite material on the recent Boeing 787 was developed on the F-22 fighter plane [10]. The interstate highway system and nuclear energy were pure government projects. The Internet were first demonstrated by universities with stimulus money from DARPA in

1969. The development of modern electronics from 1942 to about 1980 was mostly done with military funded projects. In the late 1970s, the commercial personal computer changed the marketplace as the commercial sector took off with a roar.

If you were an electrical engineering graduate in that early time frame, you probably went to work for a defense related company. The private sector ran with that electronic technical base in the 1980s and created a massive computing industry that changed world society. Government military electronic spending faded. There are many more powerful examples of government-private cooperation success especially from China, Japan, Germany, France, India, and England. Hats off to McDonalds and Wendys for selling hamburgers worldwide, and there is no record of government assistance. But when world competition and advanced technology are at stake, government alone or private alone cannot compete.

Critics Looks at Oil and Gas Future

Geologists identify the term *reserve* as the easy and economically retrievable fuel. They use the word *resource* to label the energy source that is mostly deeper and more difficult and costly to mine. Until recently, the US drew heavily from the easy reserve to reach shallow reserve pools. Today about half of American gas is drawn from traditional reserve gas domes, and the other half from deep resource fracking wells. With easy reserve fuel in depletion, the thrust is toward the more complex and expensive deep resource region. Fracking, tar sands oil, and deep ocean drilling are complex resource well examples.

Art Berman and Dan Dicker are two respected energy economists who know the gas and oil industry [11-14]. Bethany McLean is an investigative writer of books and articles for The New Yorker, Vanity Fair, and the New York Times [15,16]. All three offer critical statements about the not so long term future of fracking for fossil fuels. Art Berman is a petroleum geologist turned energy economist with over 38 years in the gas and oil business. He speaks critically to energy groups with a theme that it is all about cost. His data indicate that the bountiful fracking technique may last years, not hundreds of years. While the recent abundance of gas and oil has made them cheap to customers, that success helped lower prices below the cost of doing business. For example, if an oil company pays $70 per barrel to frack a barrel of oil whose barrel price is $34, then production stops and small companies go out of business. This is happening.

In 2020, Blomberg News published "Frackers Are in Crisis, Endangering America's Energy Renaissance" (Bryan Gruley, et al., July 20, 2020). The article reinforced the opinions of the three critics mentioned, but also wrote that the prime manufacturer of the drill rig pressure pump trucks was Frac Tech Services Ltd was in trouble of survival. They wrote that "... create a scenario in which a wave of bankruptcies in service companies leaves North American shale without enough pressure pumpers to do the work at today's standards." The drop in fuel price and the rapid decline of pump fuel flow forced over three dozen fracking service companies to file for bankruptcy. The pumps require many pressure trucks lined in series to get drive downhole pressures of the fracking fluid up on the order of 10,000 psi.

High gas prices lower demand and high demand raises prices in an oscillatory rhythm that Berman claims is about 12 months. The response is all about cost, nothing about greenhouse gases, environmental damage, fatalities, gas depletion, or earthquake avoidance. It's a business world where these "other" topics rarely rate a minute of discussion. Berman predicts that shale fracking will peak around 2025, and that might eventually drive us back to lethal coal, or a serious reappraisal of advanced nuclear generators.

Dan Dicker has worked New York energy trading for many years and is a frequent guest on cable news. He has written two books on energy including his recent book, "Shale Boom; Shale Bust: The Myth of Saudi America." [16]. Dicker has more than 20 years' experience on the floor of the New York Mercantile Exchange, where he traded crude oil, natural gas, unleaded gasoline, and heating oil futures contracts for his own accounts.

Dicker writes that the American shale fracking success is unique in the world. It has perfectly formed shale formation conditions that allowed the successful oil and gas retrieval [16]. The shale was a proper age, had an optimum relative strength between rock and soil, and a proper depth. The rock shattered when exposed to a high pressure liquid mixture. Poland, Russia, and China fracking efforts failed for lack of unique geological conditions. America also had many talented geologists and engineers and about 20 years of prior government support in the research funding, and tax incentives. Sandia National Labs developed the control system that allowed a drill bit controller on the ground surface to manipulate the drill head into a lucrative horizontal seam 2-miles down.

Shale gas optimism may be in for another shock. Thousands of gas wells report that only a small fraction of a total shale area is profitable. For example, 7% of the Pennsylvania Marcellus shale area is commercial, the Texas Barnett is 14.7%, and the Texas Eagle Ford has 17% profitable shale area. The other thousands of weak producing wells are a huge burden on profits. Extra employees must monitor and maintain this silent unprofitable array of wells and keep going where regular payments on bank loan interest and contractual obligations to landowners don't quit. The inability to predict the sweet spots prior to drilling is a major weakness. Berman states that many shale areas are available to extract gas, but only the Marcellus shale is currently profitable.

Figure 3 shows that when a gas well is opened, it emits a large transient surge of gas. The initial surge comes from the larger fractured fissures closer to the pipe followed by gas that slowly diffuses from the more distant small fissured rock. The larger volume near the explosion site empties rapidly. The extracted gas drops to 20% at the end of one year and about 5% at 4-5 years. The decline settles to a low steady level as the well deteriorates. This behavior has an easy explanation and is not denied even in the pro gas community. This fracked gas or oil property is important to understand since it imposes a limit on the ability of fracked fuel to sustain [16, 17]. It says that after 4-5 years, a new well should be fracked.

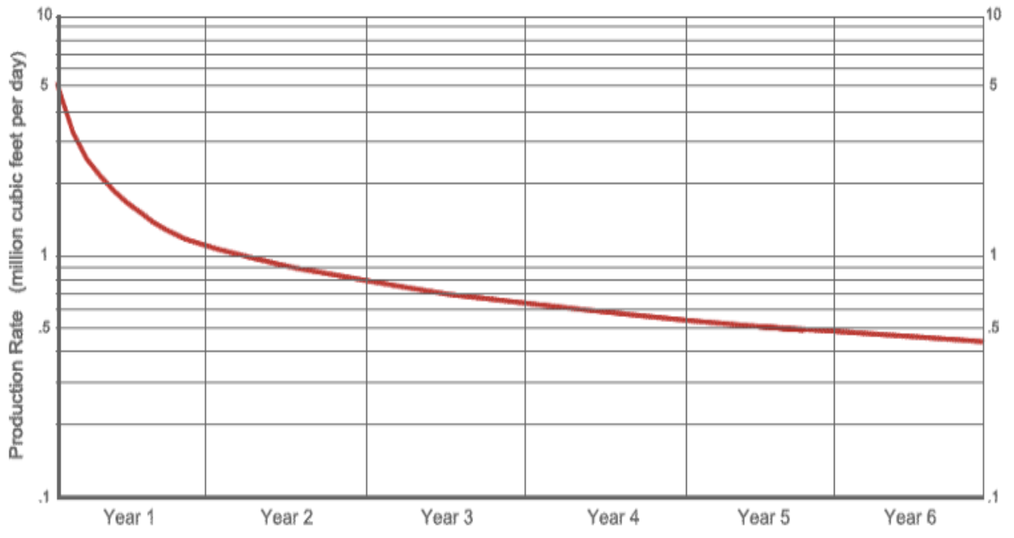

Figure 3. A gas well decline curve. Notice the depletion starts immediately and the extraction rate rapidly declines. Both gas and oil fracked wells follow this pattern. (www.geology.com)

Industry suggests that if one assumes a future steady low retrieval rate then by drilling many times the number of current wells, a total profitable amount would be obtained. This assumes that the 5% tail would go on for a long time (which it seems to do). Then if 20 wells were drilled in the one close location, then all the low tails in the curve would sum to the 5 Mcf/day of the initial single well surge. If 5,000 wells were drilled, then the field would produce 1250 Mcf/day, and gas companies think that is economic. But the calculation omits the inefficiency of one well that drains another's field.

Dicker points to the initial surge problem in shortening the projected life of fracked fossil fuels [16]. If half of the fuel taken from a well is taken by the second year and after 4 years the initial flow flattened off and is down about 95%, then the fracked well is now economically dead. That brings Dicker to conclude that the next fracking phase, and that is after 4-5 years a new well must be drilled and brought online. Fracking is unique in that funding financial sources must continue for constructing a new well every four years. It is unique to fracking fossil fuels that large capital funding must keep the process going. For this and other reasons, Dicker predicts that fracked oil will level off by 2025.

Is the US now energy independent from foreign imports? That is a wishful projection racing ahead of the facts. The US ranks 10th in proven deep resource natural gas [13]. The US lags Qatar, Iran, and Saudi Arabia. So, the question is how long US shale fields will abundantly produce at current consumption rates before we are back to increased foreign dependence.

Bethany McLain wrote "Renewables Turn up Heat on Fossil Fuel" in the New York Times, June 12, 2018, and the book "Saudi America" analyzing fracking companies on Wall Street [15,16]. The results were critical and in line with energy economists Arthur Berman and Dan Dicker. McLain quoted hedge fund manager Jim Chanos that the 60 biggest fracking exploration and production firms are not generating enough cash from their operations to cover their operating and capital expenses. These 60 firms had negative free cash flow of $9 billion per quarter from mid-2012 to mid-2017.

The major Chesapeake Company never reported a positive free cash flow from 2002 to the end of 2012. Investigation of the financial statements of 16 publicly traded exploration and production companies and found that from 2006 to 2014, they had spent $80 billion more than they received from selling oil. Only five of the top 20 fracking companies managed to generate more cash than they spent in the first quarter of 2018. The rapid decline in well flow is the primary reason for the continued expense of drilling a new well every 4-5 years.

So, what has kept the fracking industry going? One reason is that interest rates have remained low, helping companies with their borrowing costs. McLain writes that "energy independence," is in perfect harmony with "Make America Great Again." But slogans don't produce profits, and most things that are economically unsustainable, from money-losing dot-coms to subprime mortgages, eventually come to a bitter end. These are tough words, but rebuttals don't dwell on these financial issues.

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Chapter 8

Natural Gas II

–How Does it Work–

Hydraulic Fracturing (Fracking) and Horizontal Drilling

The classic way to mine for gas is to drill a vertical borehole to a depth from 5,000 feet to 15,000 feet searching for a natural gas dome. It is cheaper than fracking but was inefficient since hitting gas pockets was chancier than now, and retrieval area was small. Seismic analysis can now locate lucrative strata to a drill operator who then uses horizontal drilling to retrieve more gas and oil.

Figure 1 shows the vertical and horizontal drilling path of a hypothetical 2-mile deep well. The initial borehole at the surface is about 36” in diameter and is drilled down to about 200-500 feet just short of the water table [1]. Because the ground near the surface is comparatively soft, a metal and protective cement casing is added. As the hole crosses the water table and goes deeper, the drill bit and pipe diameters decrease with the drill bit mounted on the tip of a 40-50 foot metal pipe. The annulus between the steel casing and rock provides a return path for drill waste.

At about 9,000 feet, the vertical drill path begins a near 90^{o} bend over a distance of a few hundred feet and then goes *horizontal* for 1-2 miles inside the gas or oil stratum. The inherent flexibility of the metal pipe allows the slow curvature. It takes about 18-20 pipes to make a 90-degree bend, or about a 4.5 degree bend per 50-foot pipe. It may take about 200 pipes to make the straight vertical hole. The pipes are threaded and manually screwed together with giant wrenches on the rig platform. The drill bit is hydraulically driven with slick mud and as the drill rotates, the casing metal tubing does not. The metal piping supporting the drill bit is called a drill string.

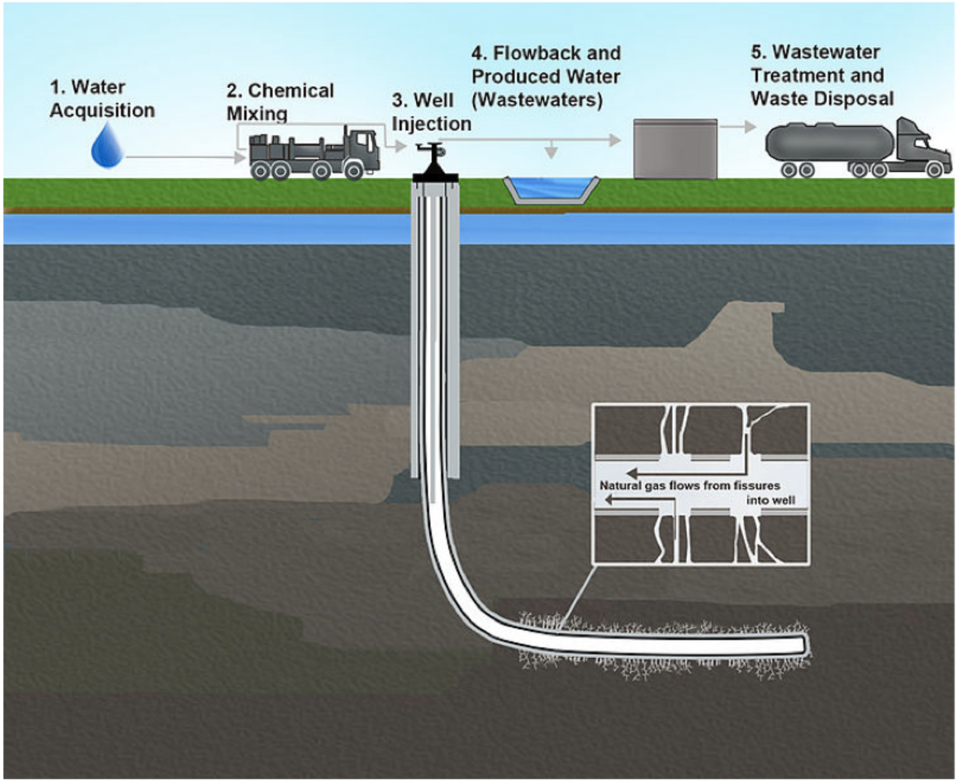

Figure 1. Drill operation and horizontal fracking. (Environmental Protection Agency)

Just before the drilling reaches a point where it would go horizontal at the curvature point, one option is to temporarily go straight down and into the target gas stratum [1]. This measures gas content and locates the optimum vertical level to enter the stratum. Then, the instruments are withdrawn and this approximately 1,000-foot vertical deep hole is filled with cement. The curvature and horizontal sections are then drilled. The drill operator sits on the drill platform surrounded by an electronic presentation of drill position and orientation. Incredible, but it works.

It’s not a one-time deal to drill a 3-mile hole and be done with it. The drill string function changes many times during the operation, and the whole drill string is continually pulled up for operations such as a drill bit replacement, a jammed drill bit, or a functional change. That means disassembling and reassembling the 50-foot threaded pipe sections for each change in the pipe string function. The hole diameter narrows as the well deepens, until the structure resembles a multi-tubed telescope. Figure 2 shows a drill bit that may last a few days before replacement. Jammed drill bits present a nasty repair.

Figure 2. A drill bit that crushes the rock with teeth of tungsten carbide and synthetic diamond. Fracking lubricant mud is pumped down the pipes and exits jets on the bit. The mud and crushed rock are forced to the surface in the outer annular region between the drill bit and casing.

There is a common word in gas drilling, and it is casing. Casing is a protective cover that can be cement or a metal as was seen in the shallow depth of the hole. A metal casing encloses natural gas on the way up the pipe, or encloses drilling, fracking fluid, or cement slurry on the way down. In the final operation, a cement casing surrounds a metal casing to provide isolation, structural strength, and double protection to the rock from pipe leaks. The quality of the casing is a strength or weakness in protecting fluid leakage into or out of the rock.

Engineering Complications

As the well deepens there is danger that the increasing downhole rock pressure will collapse the hole. Imagine the pressure on a deep cubic inch of rock. That little piece of rock must support the gravitational weight of all the two miles of cubic inches of rocks above it, all several thousand feet. If you had air at atmospheric pressure in the drilling pipe, then the high psi of the overlying rock pushes against the light pressure of air inside the borehole, and the hole would collapse. Yikes, we never thought of that!

A clever technique uses the hydrostatic pressure of the driller's mud in the inner pipe and surrounding annulus space between the rock and the pipe as a counter force [1]. If the weight density of the mud is adjusted to cause a downhole pipe hydrostatic pressure slightly more than the overlying rock, then the hole won't collapse. When you get to about 10,000 feet, that inner pipe mud hydrostatic pressure calculates to about 5980 psi. The downhole mud covers the rock surface, and the hydrostatic pressure forces the mud against the rock wall. If the mud pressure is too high, then mud leaks into the rock, and that is not good. If mud pressure is too low, then fluid leakage form outside the pipe occurs or the borehole wall will collapse. That is tricky to control and is where engineers earn their pay.

Drilling mud also works as a lubricant, coolant, and a solution to carry the drill cuttings out of the wellbore. Intermediate cement casings are installed as the drill bit goes deeper. But setting the casing is not so simple since cement must be spread in small spaces at high rock pressure with temperatures above 200^{O}F and at remote distances up to three miles from the human controller. Cement casing placement is meticulous and crucial to prevent leaks.

The next step after the drill operation unlocks the rock-bound methane gas. Perforating guns are lowered to the horizontal sections of the borehole, and then small explosive projectiles are then fired through the metal casing sidewall (Fig. 1). There are about four shots per foot. This creates holes in the pipe that are large enough to pass a second explosive operation injecting the high-pressure fracking fluid that fractures the shale rock outward to hundreds of feet from the pipe.

The horizontal section is not perforated and fracked all at once, but rather in 50-foot sections each temporarily separated by a plug of cement. The perforating guns are removed, and shale rock fissures are explosively created by pumping from 2-8 million gallons of water with up to 365 chemicals and 30 tons of sand at 10,000 psi. That is an over pressure of 4,000 psi from the rock pressure. A deeper well requires a higher fracking over pressure, more drill liquid volume, more truck deliveries, and longer drilling time. A deeper well is more expensive.

Three innovations: drilling over the whole horizontal length, fracking, and multi-well drilling from a single pad produce markedly increased gas (or oil) profits. Obo commented

> *"While fracking was the key to physically unlocking unconventional formations like shale beds, horizontal drilling was the key to making it profitable."* [2].

Methane Smokestack Emissions

Billions of dollars are being made and lost by gas and oil companies, and lesser amounts by property owners who signed off their mineral rights to mostly small, aggressive drilling companies [3]. Natural gas is now cheap, and many power utility companies are rapidly converting most of their coal generators to gas. If gas prices rise after these equipment investments, then we may be locked into an expensive energy source. We next describe the mining process, and then list the major pro arguments with rebuttals.

TABLE 1. Comparative emission gas, oil, and coal (Energy Information Agency EIA)

(Pounds per Billion BTU of Energy Input)

Pollutant	Natural Gas	Oil	Coal
Carbon Dioxide	117,000	164,000	208,000
Carbon Monoxide	40	33	208
Nitrogen Oxides	92	448	457
Sulfur Dioxide	0.6	1,122	2,591
Particulates	7	84	2,744
Mercury	0	0.007	0.016

Table 1 was shown in the previous chapter with oil data added. The oil is mostly diesel fuel. Hawaii uses about 70% oil to generate electricity on the island. There are eight major islands, and they have independent grids. This drives a renewable development pushed by lack of access to typical fuels on the US mainland.

CO_2 has an estimated half-life in the upper atmosphere of hundreds of years, while methane half-life is estimated in tens of years [3]. A greenhouse gas (GHG) practice computes what is called the CO_2 Equivalency (CE) comparing the greenhouse gas potency of a different GHG to CO_2. It can be the ratio of the potency of one ton of CH_4 released into the atmosphere compared to one ton of CO_2. The measurements of CH_4 allow a calculation that when averaged over a 100-year period, CH_4 is about 25 times stronger as a GHG than CO_2. Methane has a relatively short half-life, so the CE increases with shorter time. Over a 20-year average when CH_4 concentration is higher, CH_4 has a CO_2 Equivalency about 86 times more potent than CO_2. The CE drops in time as the CH_4 is slowly removed from the atmosphere. That is a wakeup call to worry about CH_4 leakage. Switching fuels from coal to gas does not solve the greenhouse gas emission problem.

Methane Leakage

Methane leaking is a big deal. It has a nasty property of leaking into the atmosphere and ground. Tiny CH_4 can squeeze through minute cracks or holes in transmission pipes and out of the bore hole during the drilling operation. But utility companies should have a self-interest in plugging leaks because that is lost product. Much time and effort go into collecting the CH_4, so it is more than a shame to just dump it. Robert Harriss of the National Center for Atmospheric Research listed the following methane leak sites.

- 500,000 oil and gas wells
- 493 gas processing plants
- Over 20,000 miles of gathering pipelines
- ~ 300,000 miles transmissions pipelines
- > 1,400 compressor stations
- ~ 400 underground storages

Methane that leaked from drilling or transportation was typically assumed to have negligible effects. The cry that CH_4 emitted only half of coal's CO_2 emission was enough to silence the crowd. It was like, what's a little leakage among friends. However, two recent measurement studies show that is a half-truth. One study looked at methane leaks in the older east coast cities, and the other study measured methane around the equipment sections of the gas transmission sites.

A New York City study by Gas Safety Inc. measured 247 miles of the city that has 6,302 miles of pipes transporting natural gas beneath the streets. There were more than 1,000 leaks over a 23 square mile area [4]. Methane leaked at a rate of 4.3 leaks per mile of pipe. Some of these gas mains were laid in the 19th century and were made of cast iron, wrought iron, or unprotected steel. They are susceptible to corrosion and cracking, especially in winter weather. A Boston study covered 785 road miles and found 3,356 CH_4 leakage defects for the same rate of 4.3 per mile [5].

Durham, NC had 0.2 leaks per mile and Cincinnati, OH had 0.5 leaks per mile using modern pipes. The study estimated that if the methane leakage was greater than 2% of gas quantity drawn from the well, then there is no greenhouse gas advantage of methane over coal. Last year, gas distributors nationwide reported an average of 12 leaks per 100 miles of transmission pipes (*New York Times,* March 23, 2014).

Another study measured the leakage from system hardware in the field, and the CH_4 leakage estimates increased with recent work by Anthony J. Marchese et, al. [6]. A Cornell university-industry team identified CH_4 leakage from the component equipment of the whole operation. That included equipment in exploration, production, gas gathering sites, processing, transmission, and distribution. The leakage was identified from fugitive emissions from leaky valves, fittings, and compressors; venting from normal operations; venting from periodic maintenance and upsets; and combustion emissions (un-combusted CH_4 released through the exhaust of devices fueled by NG). If you burn a cubic foot of methane, some of the CH_4 can't find an oxygen to mate with and escapes the burn and exits the exhaust as unburned CH_4.

These measurements took over 19 months at 114 natural gas (NG) gathering facilities, 16 processing plans, and 13 states. Gathering stations collect NG from many wells (10–100) and funnel this gas into a single pipeline to a refinery or to another gathering station. Over 90% of emissions were attributed to normal operation at the gathering facilities and processing plants.

There is a pneumatic regulator valve that adjusts transmission pipeline pressure and flow. Many regulators use a "puff" valve that is turned on and off. If there is too much pressure, the puffer valve vents some gas to the atmosphere. The study found that the largest emission of gas came from these valves. The puff valve is in serious need of redesign.

The Marchese results estimated that yearly leakage to the atmosphere in the US was about 100 billion cubic feet of methane [6]. David Allen, et al., reported an estimated 2,300 Gg (Gg is a million kilograms) of methane emissions from natural gas production (0.42% of gross gas production) [7]. As more wells are drilled with corresponding more leaky pipelines, the CH_4 greenhouse gas advantage shrinks. It begs the question of whether by going to natural gas, we are simply trading one greenhouse gas for another without a GHG advantage. But cost is the driver, not greenhouse gas emission or pollutants. It eats into profits when you pay for leak location and repair. Repair is happening slowly and expensively in New York City to replace aged pipes.

Northeastern Pennsylvania has serious leakage from gas wells. Anthony Ingraffea of Cornell University examined 41,000 wells drilled between 2000 and 2012 [8]. Because of flaws detected by inspectors in the cement casing of the wells, up to 40 percent of the oil and gas wells in some parts of the state may end up leaking methane.

> Ingraffea explained that the presence of methane in groundwater, and regulators who want to control its escape, now have evidence of one culprit. The authors wrote: "… compromised structural integrity of casing and cement in oil and gas wells." They reported their results in the Proceedings of the National Academy of Sciences.

A 2013 publication of the National Academy of Sciences from Duke University reported that methane was detected in 82% of drinking water samples in the Marcellus shale with average concentrations six times higher than controls for homes less than one kilometer from the fracked natural gas wells [9]. Ethane was 23 times higher for wells closer than a kilometer from the wells. To summarize, the data show gas leaks in all facets of operation. Leaks are fixable!

Methane enters the atmosphere from other sources. Billions of cows belch significant CH_4. National Geographic reported in 2016 that about 14.5 percent of anthropogenic greenhouse gas emissions come from livestock. That is more than global car and airplane traffic emissions combined. The rise in cattle related methane correlates with the increased demand of a beef eating public. Landfill areas and oil well fracking also add to the total budget.

Methane is bound in another icy molecule called a hydrate. Large amounts of hydrate exist in the frozen northern tundra regions as well as in the bottom of some regions of the oceans. Hydrates are proposed for mining but have many challenges. An overriding fear is that hydrates will melt with global warming and release huge volumes of CH_4.

Equipment on Site

The numbered sequence at the surface of Fig. 1 showed five general fracking steps. But the surface support equipment is more complex. Figure 3 shows a Marcellus well site pad that contains a large mixture of water tankers, compressor trucks, sand carrying trucks, rig assembly and assessor equipment including up to four miles of 600-pound 50-foot pipes.

Figure 3. A drilling rig site. A typical well site requires about 1,500-3,000 round trips by heavy trucks to support the water, sand, and other chemicals. The drilling goes on 24/7. A typical complete drilling and fracking operation can take 1-2 months. A well site footprint needs about 5 acres. (Schlumberger).

The hydraulic fracturing, or fracking, shatters the rock creating large and small fissures that may reach out from the pipe to hundreds of feet. After the fracking explosion, the high natural down hole pressure and high temperature gradients drive the gas and fracking fluid up the borehole for surface collection. Gas is released in the downhole rock fissures that are held open by sand grains called proppants. Gas travels rapidly through larger cracks in the rock, and slowly through the smaller fissures and unfractured rock. So, there is an initial high surge of gas from nearby large cracks followed by a smaller flow from distant tiny cracks. That is true of gas and oil. That surge behavior is crummy, but predictable.

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About 30%-80% of the original six-million gallon downhole fracking fluid and associated downhole product water are forced back to the surface when the fracking surface pressure is released. Some fracking fluid is recycled, but the rest must be collected and stored in a protected containment. Large metal tanks, holding ponds (Fig. 4), abandoned drill sites, and deep disposal wells absorb the toxic brew. The Marcellus shale does not have the deep storage basins of Oklahoma and Texas. Later we will site the storage millions of gallons of fracking fluid in the western disposal basins as the source of fracking related earthquakes.

Authors Eric George and Gary Serovitz worked in the fracking industry, and their books make the case for not putting fracking or fracking critics into a make-believe bad image [3,4]. I believe George when he says that many engineers work hard for quality cement casings, leakage control, and concern for fracking fluid waste. And he points out that not all companies have that culture. Alex Prud'homme's statement that, "Individual energy features are not all bad or all good." does not imply that all energy techniques are equal [5].

Figure 4. A wastewater fracking holding pond is typically located near a Pennsylvania farm or house. The river in the upper left was measured for toxins and elevated levels in a study that found chloride and bromide, combined with strontium, radium, oxygen, and hydrogen isotopic compositions present in this Marcellus Shale water, www.thesleuthjournal.com.

Low Cost Comments

Profits were recently in the news. The Business Section of the Atlantic Magazine in their January/February 2017 issue reported a dramatic decrease in the cost of fracking. They wrote that the continued low price of gas at the pump was caused by US fracking production and an OPEC desire to drive frackers out of business if OPEC lowered barrel prices. OPEC with large reserves could outlast the more expensive fracking oil.

100 North American oil and gas companies went bankrupt in 2015-2016. But recently a break even cost that was $69 per barrel in 2014 was reported as beat down to $29 per barrel in the Bakken in late 2016, and the OPEC threat was over. That is challenged by Art Berman who thinks $50 is more realistic when we include all costs [10].

Some frackers reported that cost cutting techniques reduced the average drill time from 25 days to 15 days in the Eagle Ford shale. They focused on the most productive areas of a shale region and examined each step in the process for improvement. Electronics and mechanical product manufacturing historically call this climbing up the learning curve.

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Chapter 9

Natural Gas III

–More Downsides of Fracking–

Shale wells have high decline rates and require substantial capital expenditures to keep extraction rates flat much less increasing. Creating thousands of crappy little wells is a loser.

- Arthur Berman, Energy Economist

It's now time to reach to the next level that will polish off your skills in debating the place of natural gas in our future diet of energy. A natural gas well is an organic synchrony of men and equipment. It grows, reproduces, has bad breath, defecates crushed rock, vomits fracking fluid, shakes the Earth, has an intestine that growls and passes gas, can be noisier than a Friday night happy hour, but it cannot provide dependable power to large populations. We will start with financial advisor John Graves who presents a positive case for fracking shale gas from the upper management view [1].

The Happy Side of Fracking –Another Look

John Graves's positive list includes: gas does not emit the many hazardous toxins of coal; the dual-cycle gas electricity generators couple a gas turbine to a steam generator and see efficiencies of 54% or more; gas creates so many jobs that the gas fields cannot hire enough for their demands; the associated natural gas liquids (NGL) of ethane, propane, and butane are essential for our petrochemical industries; the US will be energy independent; the casing seal in the borehole prevents fracking fluid pollution and methane migration; worker safety is increasing each year; multi-well drilling from a single pad reduces truck traffic and expenses; positive impact on environment with about 50% less CO_2 emission than for coal; the US in the only country to reduce greenhouse gas (GHG) emissions since the Kyoto Treaty despite not signing the Treaty; many landowners have risen from low income with the lease and royalty money; the US is exporting natural gas (NG) as LNG (cold Liquefied Natural Gas) ; and equipment reliability is high [1].

The Other Side of Fracking –Another Look

The word "However" should follow most of these happy statements, as they often hide the whole truth. Sentences may be literally true but mislead. For example, Rao compares the following two true sentences [2]. "Hydraulic fracturing (defined as the down hole explosion of rock) has never caused aquifer pollution" versus "Wells polluted by the hydraulic fracturing *operation* have caused aquifer and domestic pollution." Another example is, "The US has at least 150 years of gas *resources*" –maybe true. "The US has about 10-30 years of economically retrievable gas *reserves*" – probably true.

The anti-frackers also hyperbolize. For example, "Gas drilling injects methane into water faucets causing fires" versus, "Polluted wells from gas drilling allow methane into *some* water faucets causing fires." Another example: "Fracking causes earthquakes" versus "The heavy fracking wastewater put in deep underground disposal sites can cause earthquakes in *some* injection wells, if the fault geometry is vulnerable."

A large coal plant emits about 3.5 - 6 million tons of CO_2 per year, so one gas power plant would emit just under 2 - 3 million tons of CO_2 per year. The total utility plants in the US emit about 1.7 billion tons of CO_2 per year. The thousands of diesel truck fracking deliveries emit considerable CO_2 and soot particles driving up the numbers. But methane does not emit the many toxic coal chemicals, and that is emphatically good. Methane does not kill or injure as many people as coal, and that is also good. Methane power can couple a gas turbine whose hot exhaust drives conventional steam generators almost doubling the fuel efficiency.

Obo describes the dangers of leaked fracking pollutants, and states that better regulation and safety rules are the answer [3]. But given the abundant reports of pollution, simple regulation is not the answer. The gas drilling industry does not show the quality culture of the aircraft, electronics, space, medical, nuclear, or automobile industry. At least they have not communicated it authentically to the public where company advertisements and YouTube videos don't count.

Methane Gas Accidents

Leakage induced methane explosions are powerful and often. For example, an explosion killed eight people and destroyed an apartment building in East Harlem in 2014. Another gas problem appeared on Oct. 23, 2015, when a massive natural gas leak erupted at a storage well at Aliso Canyon near Los Angeles. About 100 Mega ton of natural gas escaped to the atmosphere. There many historic examples, but these explosions should be kept in mind when later we address accidents of older nuclear reactors.

There were 941 significant natural gas incidents from 1994 through 2013, resulting in 363 fatalities, 1392 injuries, and $823,970,000 in property damage [4]. That is an average of 47 serious gas incidents per year. A *Wall Street Journal* review on January 20, 2014 found that there were 1,400 pipeline spills and accidents in the U.S. 2010-2013. According to the review, four in every five-pipeline accidents were discovered by local residents, not the companies that own the pipelines. Natural gas is colorless and odorless making it difficult to detect. The gas utility that delivers to your home puts a smelly chemical called methyl mercaptan into the gas. It has a distinct rotten egg smell that excites you do something about it -it is leaking gas.

Methane Migration

Methane exists under high pressure in pockets deep under the ground. This pressure gradient can drive methane to regions of lower pressure even in materials of low permeability. Engineers know that given a strong pressure gradient, CH_4 can travel up the borehole if the casing had an imperfect interface. It might take weeks or years, but it will happen.

Defective liners allow methane to migrate to domestic wells, basements, and aquifers. Several bad examples occurred in the Marcellus shale especially in the village of Dimock, Pennsylvania [5].

Tom Wilber described accidents in Dimock [5]. In July of 2008, a truck knocked over a storage tank spilling about 700 gallons of diesel fuel. Later a truck crashed into a yard causing a gas line leak. In September of 2008, that same house reported brown water in their domestic well, and their house water and laundry were brown. In December of 2009, a domestic well in Dimock exploded, and in July 2008 an explosion killed a couple and their grandson. There were many other such incidences in the Marcellus shale [5]. The Cabot Company that drilled the gas wells denied blame.

There are many other incidents of natural gas leaks into the air and water table. Not all fracked wells leak, but when they do the effect can be devastating. Methane and fracking fluids can find their way into human and animal exposure. There is a further story to tell, and it occurred in Washington County in Southwestern Pennsylvania affecting several families [6].

Eliza Griswold is an award-winning author who wrote Amity and Prosperity: One Family and the Fracturing of America [6]. It researches the severe human health impact, farm animal deaths, and financial devastation on families in Southwestern Pennsylvania.

Stacey Haney is a single mother of two children who became the center of a seven-year struggle ending in the Pennsylvania Supreme Court over a citizen's right to clean air and clean water [6]. Can a business or industry move into a residential or farm locality, overcome weak or nonexistent Planning and Zoning Rules, and pollute air and water? Should surrounding homes be required to go to

Walmart to buy bottled water. As a minimum, shouldn't the offender pay for pollution related medical expenses? Do property owners have the legal right to be protected. Should the death of farm animals go unpunished? Does a company have this right?

Stacey Haney and her children acquired serious health issues that were contested by a billion dollar Texas gas company Range Resources, who denied responsibility for major damage to Haney and her neighbors. Eliza Griswold reproduced a statement in her book that Haney posted on her door that expresses the frustration and rage over the fracking well related damage to Haney and her children's lives [6].

> *TO THE IGNORANT MOTHERFUCKERS who keep breaking into my house: it's bad enough that my children and I have been homeless for 2 and a half years but now I have to deal with this. Your greediness has cost me over $35,000 in damages and the bank has put a forced insurance of $5000 on my mortgage, so as of Jan 1, my mortgage payment goes up $500 a month. I hope you feel good about what you have done, and I hope you know that the contamination in this house causes cancer, so keep coming back you fucking losers. I hope you rott with cancer!!! And when your spending all your scrap money I hope you think about what you are taking away from my children.* —A note Stacey Haney posted to the door of her abandoned farmhouse on November 3, 2013

The air-water pollution began when Range Resources drilled a frack well about a quarter of a mile from the Haney house. The well was on a hill so that leakage from their wastewater pond went into the ground and gravity expedited moving polluted fracking fluid onto the Haney property. The pond had a double covering for extra protection, but it leaked. The best guess behind the leak was that two deer had gotten into the pond and their hooves damaged the coverings. In the end, Haney's farmhouse was unlivable, unsaleable, and later destroyed.

The Pennsylvania Supreme court voted in favor of Haney and her neighbors, but the plaintiffs were never adequately compensated for their life destroying experience. The majority of us don't have this experience and can at best express sympathy. But remember this when you read about how fracked gas is the safe bridge to an energy source beyond coal.

Methane Flaring Waste

Significant gas can leak when the well gas is first connected to the transmission pipe at the ground surface. When well gas capture and transmission pipes don't exist for the methane in an oil well, the gas goes into the air. This is a form of venting. Intentional venting of oil wells and igniting the escaping gas leads to large continuous flares. This is energy wasteful and unnecessarily contributes to GHG emission.

How Long Will Natural Gas Reserves Last

Both sides roughly agree that the total amount of available gas beneath the Earth (the gas resource) is large. Resource projections estimate from 100–250 years of usage, although there are serious challenges that the actual total may be much lower [7,8]. The economically retrievable gas may be in the range of 10-30 years. Experience shows that as you go deeper, the conditions worsen, and the quality of fuel gets worse as we run into contaminants. Water gets saltier and the magma radionuclides appear. Gas corporations need investor money and may not get it if they spoke of gas reserves of 10-30 years. So, advertisements and political messages often reflect extreme views. There is passion on both sides of the argument.

Let's use data to calculate how much US gas is left using estimates on proven reserves and resources from the US Energy Information Administration (EIA). In 2015, gas in the US had a consumption rate of 27.31 trillion cubic feet (cf) per year. The resource volume was estimated at 750 trillion cf and reserves were 324.3 trillion cf. If we divide each volume estimate by the consumption rate, we get the expected life of each volume. The resource volume would last 27.5 years, and the reserve volume would last 11.9 years for a sum of 39.3 years. That is not hundreds of years. And it is not realistic that we can pull out every last molecule of remaining methane, so the estimate from EIA data is less than 39 years. Cost will determine when we have run out of natural gas.

And it is not the popular statement that we have hundreds of years of natural gas, especially since we can't guarantee that all gas resources are even economically retrievable. That is significant. If gas replaces coal, we may shortly be looking to replace gas. *Those who predict hundreds of years of gas access must show data at this point and not just look at a shale map.* David Goodstein describes in his book Out of gas that the oil crisis will not occur when the last molecule of gas is extracted, but when oil extraction can't meet demand – perhaps as soon as 2025 [9].

Gas Well Production Decline Rapidly

How can we decide the fate of gas that many believe should be the dominant base load energy? Let's dig deeper. The shale areas of Barnett (TX), Eagle Ford (TX), Marcellus (PA, NY, WV), Bakken (ND, MT, Canada), Utica (NY, OH), Haynesville (AR), and others cover thousands of square miles. But we know from Barnett and Marcellus shale data that only a few counties in each shale region are economical to operate [7]. There are only 2.5 counties out of 17 (15%) in the Barnett play that operate economically. The Marcellus region in Pennsylvania shows similar small "sweet spots" that may be found in only 6% - 7% of the wells. If we use the average rate of gas drawn from these sweet spot wells and then assume the same average rate for the whole area, then we get a large and unrealistic estimate.

Figure 1 shows data from the EIA of cumulative decline curves for five shale plays. The decline time is similar to that of a single well. The upper right of Fig. 2 shows a cumulative plot for total gas retrieval. In each well. At the end of 20 years, most of the gas has been pulled from each well if no new wells are added. The curves show why it is not surprising that most shale plays are leaning to unprofitable. *These data fly in the face of long term investment of frack based natural gas and oil.*

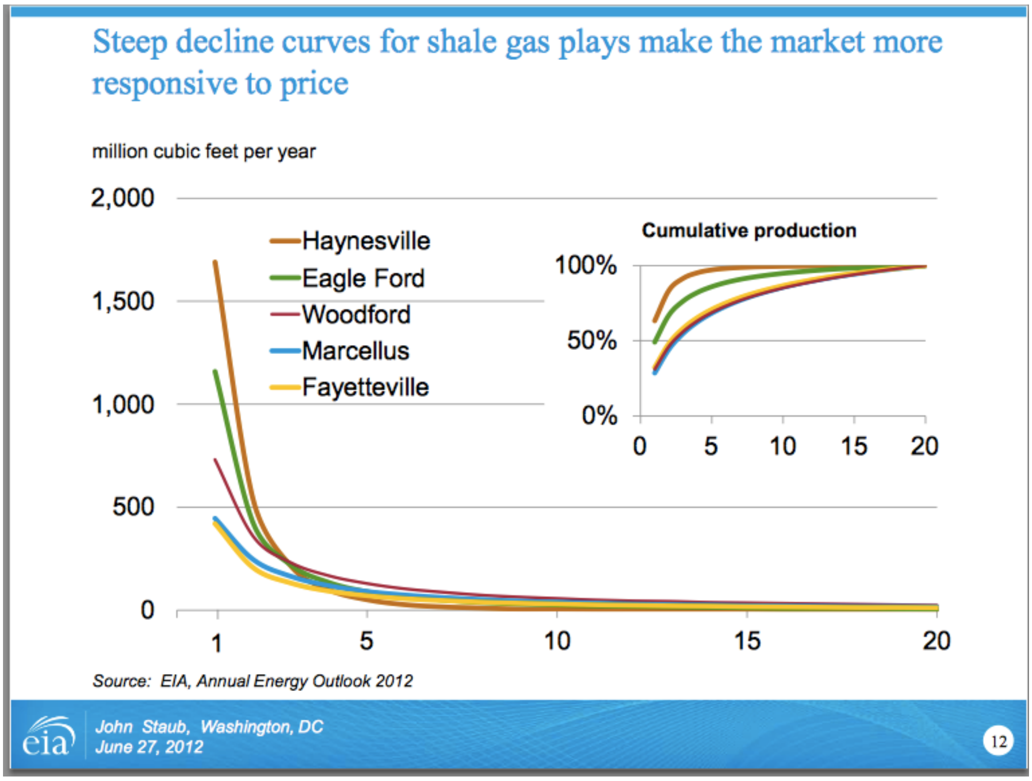

Figure 1. Decline of five shale gas wells in years. (EIA, Annual Energy Outlook 2012)

Drilling more compensating wells is edgy since each new well can cost over $5 million dollars. Well drilling would be unending and increasing the current number of wells by 20 times would be geographically challenging in most states. A current practice is to drill six or ten separate wells at the same location. Many more wells can be drilled within several feet of the original well, and there is footprint savings in having to just drill one pad. The direction of the horizontal drilling can spread out to minimize draining gas from another pipe's region. But it is a design that multiplies the effects of methane leakage, water contamination, heavy truck traffic, fracking fluid related earthquakes, and yet still has a relatively short productive life of its own (Fig. 1).

Future Gas Economics

Arthur Berman states that it is not economic to continuously support wells with low output. In his blunt words, "Shale wells have high decline rates and require substantial capital expenditures to keep extraction rates flat much less increasing" [7,8]. Dan Dicker predicts the trend of increasing rig count and fracked wells will level off by 2025 [10]. A functioning well has operating expenses, overhead expenses, high interest rates on loans, and these factors work against the profitability of low producing wells. Contracts with property owners often specify that pulling gas from the well, however small that may be, shall not be terminated. The landowner at least makes some profit off the low producing wells while the company does not.

If the market price of gas rises, then more wells become profitable. But as gas market price increases, then competition from coal and nuclear increases and eats into gas profits. Investing billions of dollars is high risk in what may be an unproven short-term energy source. The eternal hope is that industry will develop new technology just like the horizontal fracking technology in the 1990s. But as the saying goes, "Hope is not a plan."

Other Fracking Variables

Each shale region has unique properties that affect the cost and complexity of the drilling and gas retrieval. A deeper well is more complex and expensive. Deeper wells require more water, more truck deliveries, higher fracking pressure, more pipe and cement casing at a higher pressure, more fracking fluid to dispose, and take longer to complete.

The pump trucks for deeper wells must further increase the fracking pressure to overcome the downhole earth pressure that increases with depth. The shale rock hardness varies making it costlier to drill. There is a well depth limited by these variables.

The gas shale strata vary with each region, and this causes well costs to vary as parameters vary. Prud'homme cites the different shale strata levels [12]. The Marcellus shale depth averages about 6,200 feet, and costs about $5 million per well. The shale depth in the Andoka-Woodford shale ranges between 11,500 – 14,500 feet, and the average cost to complete a well is about $8.5 million. Much of the Utica lies 3,000 – 7,000 feet *below* the Marcellus. The Bakken shale depth ranges between 3,000 – 11,000 feet while the Fayetteville shale ranges from 1,450 – 6,700 feet. The Eagle Ford shale has a larger range of 4,000 – 14,500 feet. The

Haynesville shale averages about 12,000 feet with downhole temperature over 300^{O}F and a rock pressure of over 10,000 psi. This higher rock pressure demands a higher truck pump pressure.

Prud'homme approximates fracking water consumption of a shallow well at 65 kGal/well, and a deep well at 13 MGal/well [12]. The Marcellus shale has no empty subterranean basins to store waste frack fluid, while Oklahoma and Texas shales have deep storage basins.

Let's take a short side trip from fracking and ask how deep can we drill? With all the talk about drilling a hole from 1-3 miles, you may have wondered. The cold war between Russia and the United States was active in the 1970s and science competition was important to each country's image. In the 1960s, the US funded a deep hole project called Project Mohole, but it died in 1966 with follow on projects being its major contribution. Russia funded a successful deep hole drilling from 1970-1992 called the Kola Superhole Project. Kola is a village in the far northwest region of Russia on the Bering Sea.

Over a 20-year period, the Russian hole went to 12,066 m (7.6 miles). It was stopped when the equipment could not cope with the high 180^{o}C (356^{o}F) temperature. The drilling mud was boiling with hydrogen, and the rock had a plastic consistency. If the rock pressure is about 6,000 psi at 2-miles, then we can extrapolate that the rock pressure is about 22,830 psi at 7.6 miles down. The goal was to drill as far as possible with a 9-inch borehole diameter.

The Kolo project fell well short of drilling through the Earth's mantle to the magma, but it did find 24 microscopic plankton fossils at 4-miles, and the rock went from basalt to granite below 4.7 miles. Water was found between 2 and 4 miles down trapped in the rock. Two years later the US deep hole drilling experiments beat the Kola by a few meters, but the Kola Project often still gets the credit. Now, back to fracking.

Fracking Fluid Pollution

The flowback fluid just after the fracking explosion contains the chemicals used in the fracking plus those Earth minerals and salty water absorbed from the deep fracture zone after the fracking explosion [12-14]. The fracking fluid absorbs chemicals from that depth that include uranium, radium, thorium, salty water, and radioactive potassium. The frack chemicals injected include hydrogen sulfide, biocides to kill deep bacteria, chlorides of sodium, magnesium, calcium, iron, iron, barium, strontium, manganese, and methanol, chloride, sulfate, benzene, toluene, ethyl benzene, and xylene. These chemicals constitute a miserable mess, and something must be done with them.

There are several Marcellus disposal methods. Fracking fluid may be piped to temporary surface holding ponds where the water can eventually evaporate leaving a solid frack for truck removal. Or, it can be partially recycled and used by injecting down another well. Figure 2 shows a retention pond in the Marcellus shale in Pennsylvania. Notice the proximity to the houses and forest. So much for low impact on environment.

Figure 2. The Marcellus shale illustrates the impact of fracking in rural areas. Holding ponds are often located close to the farms and houses.

The major methane advantage over coal is that gas does not kill or sicken as many people as coal, gas does not emit the toxic chemicals, coupled gas turbines almost double the efficiency of coal, and gas does not have the cumbersome coal rail transport and scrubber systems. But gas emits half of the CO_2 of coal, gas is leaky, greenhouse gas sensitive, CH_4 is explosive, it has fracking's death and injury rates, and a well has a short life span of about five years. it has environmental downsides, and its data-based projection time is less than 40 years.

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Chapter 10

Natural Gas IV

– Some Last Topics –

It is difficult to get a man to understand something when his salary depends upon his not understanding it."

- Upton Sinclair in "The Jungle" circa 1905

There are a few more topics to clean up, and the first one will be gas turbines instead of steam turbines.

Gas Turbine Electricity Generators

Gas turbines have three major sections; an input compressor, a combustion system, and a turbine [1]. The compressor sucks in air and pressurizes it before feeding the gas at high velocity into the combustion chamber. The hot burning gas from the combustion chamber drives the turbine. The latest gas generators reach a turbine driving temperature of 2600 ^{o}F with efficiencies of about 60%. Older generators reach 2000 ^{o}F with lower 30% efficiencies.

Gas generators come in two designs: heavy frame engines and aeroderivative engines. The heavy frames have higher output power, but lower efficiency. The aeroderivative engines are smaller and designed like a jet aircraft engine. They have higher efficiency, but lower power output.

Dual-Cycle Electrical Power Generators

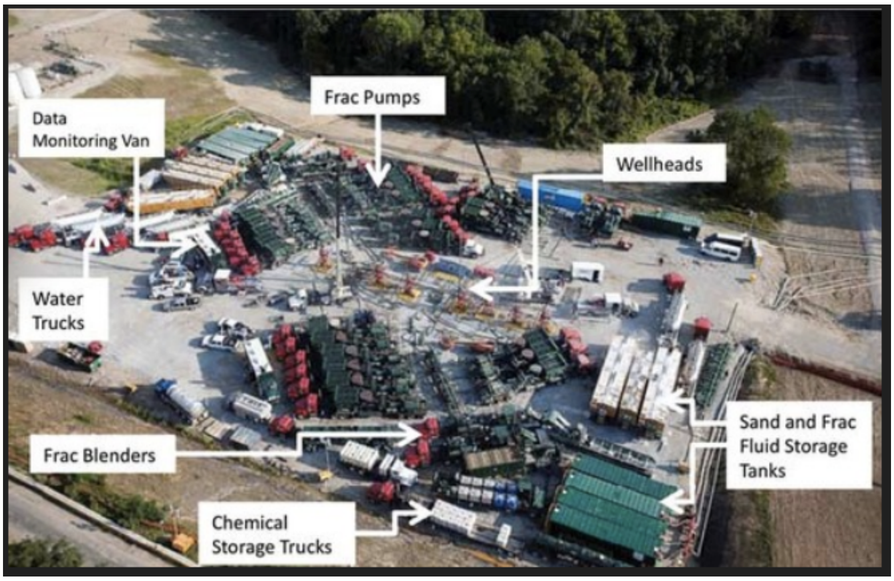
A *recuperator* is a boiler that collects the hot turbine exhaust gas and drives a steam generator forming a coupled system that can be purchased as a unit. Coupled efficiencies of up to 60% are reported. Exhaust gas from the steam generator can further heat buildings or be used for other industrial cogeneration operations. Efficiencies nearing 80% can be achieved with that combined cycle cogeneration operation. This is huge and exciting news that saves burning a lot of gas and big chunks of coal.

Thus far, individual coupled generators are capable of only 150 MW to 200 MW. But industry has raised the power outage by using two or four gas turbines in parallel to thermally drive one steam turbine. If each of four gas turbines generates about 150 MW, and the steam turbine about 450 MW, then a GW is generated. Florida utilities are rapidly adopting this multiple generator strategy [2]. It is a fuel saver in a developing technology.

Transport Trucks

A single drilling and fracking operation requires about 1,500-3,000 trucking round trips depending on shale variables [3-5]. Some fracked gas wells lie in towns and cities and even on the grounds of the Dallas-Ft. Worth airport. Many of the Western US shales in Oklahoma, North Dakota, Colorado, and Texas exist in relative flat land and low human population. The Marcellus shale in Pennsylvania is the opposite. The hilly and curvy county roads are paid for by local taxes, and these roads were not designed for such heavy trucks and dense traffic. Some companies pave the roads before and after the drilling operation. Figure 1 (a) shows a rig site truck assembly, and Figure 1 (b) shows a Google Map photo of a completed well pad. The drill site is crowded, noisy, smelly, and works all night with bright Klieg lights.

(a)



(b)

Figure 1. (a) Truck and other equipment complexity at a single drill site. The work goes on 24 hours per day, seven days per week. (Photo from Kansas Geological Survey). (b) A Google Map satellite close-up of a completed well pad in Pennsylvania (Google Maps).

Frack Related Earthquakes

Earthquakes are linked to hydraulic fracking around the world [6-9]. Germany, Switzerland, Ohio, Texas, Oklahoma, Colorado, Texas, and California report fracking related earthquakes. The Dallas-Ft. Worth area had never had an earthquake, but since 2008 has had about 200 earthquakes. Oklahoma had a similarly low rate of earthquakes until its 890 earthquakes in 2015.

Millions of gallons of wastewater per drill site are stored in nearby deep disposal wells. Western states have abundant caverns deep underground to inject the wastewater. Oklahoma has about 3200 disposal wells. Over 20 million gallons of wastewater are stored in a disposal well, and this weight and lubrication can perturb a vulnerable fault causing a fault slippage and an earthquake. The fracking explosions themselves can cause mild earthquakes but less than Richter-3.

A Richter-3 earthquake is one that is slightly felt. A 4-earthquake on the Richter log scale is ten times that of a gentle 3-Richter, a 5-earthquake in 100 times stronger, and so on. Recently, an Oklahoma 5.6 followed a 4.6 earthquake in Prague, OK. On the Richter Scale, a 5.6 is about 400 times stronger than a mild 3.0.

Rivka Galchen wrote of the recent epidemic of earthquakes in Oklahoma [6]. Before 2008, Oklahoma averaged 1-2 earthquakes per year larger than 3.0 magnitude on the Richter Scale. There were 20 such earthquakes in 2009, 42 in 2010, and 585 in 2014. In the first four months of 2015, there were an average of two earthquakes per day of 3.0 or larger. Youngstown, Ohio had over 109 small earthquakes from 0.4 to 3.9 Richter scale between January 2011 and February 2012.

Gas proponents precisely define fracking as the deep underground explosion that fissures the rock, and with that redefinition will say that fracking does not cause earthquakes [7-9]. But this distinction is not relevant when addressing a solution, and we can't lose sight that without fracking there would be no induced earthquakes.

The Marcellus shale has smaller earthquakes in the range of Richter 2 - 3.5. Since the Marcellus does not have the deep caverns to store fracking fluid, it is thought that these smaller earthquakes arise from the fracking explosion of the rock itself.

William Ellsworth, a research geologist at the United States Geological Survey says, “We can say with virtual certainty that the increased seismicity in Oklahoma has to do with recent changes in the way that oil and gas are being produced.”

Landowner Income

Drilling companies quickly move into regions when shale gas is discovered. People known as landmen knock on the homeowner doors to obtain leasing and royalty licenses for the companies [10]. They must lease the mining rights from small property owners before competitors do. They lease hundreds of thousands of acres investing up to a billion dollars. It is labor-intensive to negotiate with so many landowners, and it can be a one-sided business since owners may have little knowledge of the potential wealth that may lie beneath their land.

Tom Wilber interviewed many property owners where initial leasing rights in the Pennsylvania Marcellus Shale went for $25 per acre, and later with landowner experience the fee went as high as $2,500 per acre [11]. It all seemed to the homeowners like a clean way to earn large sums.

But then the big trucks, tree removers, land graders, and drilling equipment arrive, and the operation goes 24/7 with bright Klieg lights at night. Fracking fluid, wastewater pits, airborne pollutants, accidents, noise and odors arise. Buyer’s remorse is common especially for those whose property yielded low gas. Those who strike it big seem content and sometimes angry with neighbors who publicly complain. While owners are responsible for what they signed, the gas company landmen often obscure the realities and may use high-pressure arguments to close a deal.

Job Creation

The gas industry cites job creation as a plus in shale development. The Pennsylvania Department of Labor and Industry reported 28,926 workers in the Marcellus oil and gas industry in 2015. It counted jobs in drilling, extraction, support operations, pipeline construction, and transportation. 28,926 jobs are 0.5 percent of the 6 million workers in Pennsylvania. By comparison, nearly 1 million state residents worked in healthcare, 490,000 jobs in education, and more than 134,000 in state government. While gas & oil fracker jobs are important, they are not close to dominating and most are not career jobs. Hooray for gas jobs, but when the boom is over so are most jobs.

The shale gas and oil industry support a service industry that also employs truck drivers, rig workers, and disposal operators. John Graves describes MBI Energy Services in North Dakota that has a fleet of 1,000 water trucks and operates 48 disposal wells [10]. Nuverrsa Corp. is another employer in North Dakota that transports fluids and solids.

The average number of workers on a rig team was estimated at 11.5. Rigging jobs demand persons with exceptional strength and endurance (Fig. 2). The work is done outdoors in all weather conditions. North Dakota, Montana, and Pennsylvania winters can be brutal, while Texas and Oklahoma have cold winters, windy springs, and sizzling summers.

About two years after intense drilling began in the Marcellus, 70%-80% of the work force typically came from southwestern shale states. Temporary “Man Camps” housed the workers. Working conditions were a culture shock to most native Pennsylvanians, and a high turnover rate occurred. One study found that over a 1.5-year period, seven workers were hired for one slot. Across the country military veterans were considered better hiring choices, since many had experienced hard conditions in the service. The fatality and injury rates make it a dangerous job.

Figure 2. Rig workers in slippery conditions use large wenches to couple 50 foot threaded pipe sections. (www.cnn.com)

Worker Safety and Fatalities

Worker injury and death occur in the field drilling operation and in the material transportation and chemical handling. Heavy tools, 600-pound pipes, and high-pressure lines are constantly maneuvered in rig platforms often covered in slick drilling mud and extreme weather conditions.

The following fatality data were taken from the National Institute for Occupational Safety and Health (OSHA) and the *New York Times* for gas and oil drilling, since both now use fracking. Oil and gas support activities in the US had a spike in deaths with 58 in 2011, up from 48 in 2010 and 27 deaths in 2009. Of the 716 oil/gas worker fatalities that occurred during 2003-2009, the majority were either highway motor vehicle crashes (29%) or workers struck by tools or equipment (20%). The next most common fatal events were explosions (8%), workers caught or compressed in moving machinery or tools (7%), electrocution, gas explosions, blowouts, shifting metal pipes, and falls to lower levels (6%).

The Houston Chronicle reported that 65 oil and gas shale workers were killed in Texas in 2012. This was a 10-year high and 50 percent more than in 2011. About 18,000 oil and gas workers suffered either amputations, were crushed, burned, broke bones, got cut, or reported other kinds of work-related illnesses from 2008 to 2013. This is a side we don't see as we pull into a gas station and, "fill it up." The phrase Clean Gas doesn't look so clean up close.

Highway crashes often involve over-worked and fatigued employees driving vehicles after long shifts allowed by regulatory exemptions for the oil-gas industry in 2001. Fracking increases the normal risk, since it leads to more trucks on the road due to the millions of gallons of water and tons of sand used per well. About 42 percent of workers in the mining industry are considered sleep-deprived.

Frack Sand and Silicosis

Silica is fine sand that is used as a proppant to hold open rock fissures created by the fracking explosion. Silicosis is an occupational lung disease caused by inhaling crystalline silica (SiO_2) dust. It causes lung inflammation and scarring.

OSHA collected 111 personal breathing samples at 11 sites in five states to evaluate worker exposures to respired crystalline powdered silica ("frack sand") during hydraulic fracturing. At each of the 11 sampled sites, exposure exceeded the OSHA and NIOSH (National Institute for Occupational Safety and Health) safety thresholds in some cases by 10 times or more.

Environmental Degradation

There are many descriptions of the number and density of gas wells in many states. Could a Google Map show these, and indeed it can. Figure 3 shows a Google satellite view of Bradford County, Pennsylvania in the Marcellus shale with eight gray rectangular gas pads. Not all Marcellus regions are this gas well dense, but it's hard to miss the point unless you are a big city person who doesn't get what anyone sees in country living. New York state prohibits fracking.

Figure 3. This roughly one square mile of Bradford county Pennsylvania land shows eight completed well pads (small gray squares) and two retention ponds not yet cleared. Notice the narrow winding country roads and proximity to farmhouses. (www.Google Maps.com)

Bamburger & Oswald, and Wilbur wrote of personal inquiries at these farms [11,12]. The results are similar. For some there are no complaints, but there are too many detailed descriptions of families in the Marcellus Shale who have suffered loss of livable land, human and animal death and sickness, ruined potable water, land that cannot be sold, and foul sickening air. An energy executive cannot blithely dismiss them as collateral damage.

Bottleneck Problems on the Gas Pipelines

The Permian Basin in West Texas and Southeastern New Mexico is America's largest oil dome. It has been producing since the 1920s. But depletion reduced the output of oil and gas, until fracking rejuvenated its output. Figure 4 shows the density of oil pumps in West Texas. If you sit by the window on a flight from

Houston to Phoenix, you get this view and even more. Although Texas has about 2.4 million miles of energy pipelines, an overabundance of oil could not be transported because there wasn't enough pipe capacity. Fuel stacked up and its price dropped. The Eagleford play in Southeastern Texas had easier transport to oil tankers on the Gulf of Mexico and the local price rose. The oil industry claims the problem is temporary. The fuel led to an increase in transport by truck and train. Maybe, but when fracking profits are hard to come by this is another clog in the works.

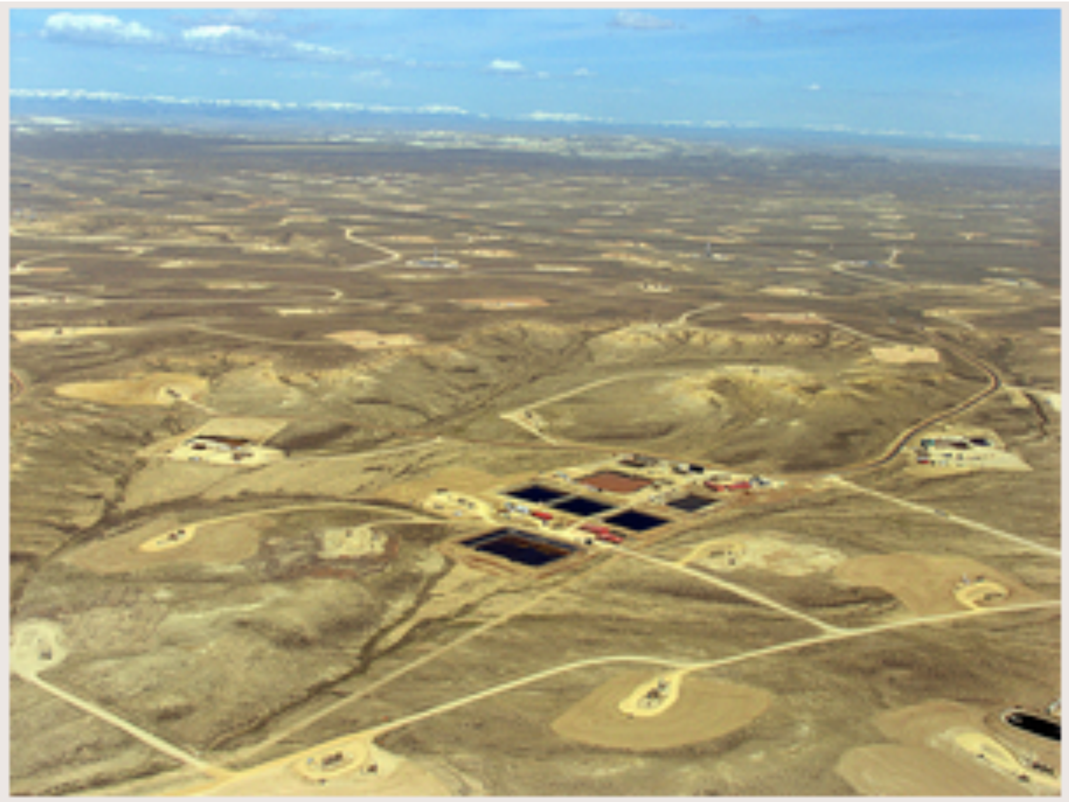


Figure 4. A cluster of fracking wells in the west. http://ecoflight.org/

Summary

Modern fracking began in the late 1990s. The technology is still evolving, and this presents a moving target. But some features are clear. The fracking operation is complex, expensive, dangerous, and prone to serious environmental damage. Some feel that the gas cat is out of the bag, and it is too late to slow it down to consider solutions to its weaknesses or renewables [13-17].

When we dig beneath the advertising of gas as a clean energy bridge from coal to renewables, there are unanswered questions. The coupled gas-steam- building heating system really increases the fuel efficiency, but abundant reports of ground water contamination, surface pollution, plundered landscape, methane leaks, greenhouse gas emission, earthquakes, short term fracking life, and gas explosions are too many and too real to ignore.

Will these serious objections be rectified? Will sound engineering address costly leaks? Will true safety practices ever prevail in the gas industry? The methane leakage and safety issues are solvable with focus and money, but despite capability to fix these serious problems, we might continue down the path we are on and give lip service to solutions. And finally, there is the question of short term availability of gas and oil in the 10-30 year range and not hundreds of years.

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Chapter 11

OIL

Burning oil to make electricity is like washing your dishes in French champagne

-Anonymous

When oil has more important uses in fertilizer, plastics, and automotive manufacturing, why burn it when other paths exist? It seems unusual to burn oil for electricity, but isolated locations without pipelines or coal trains use oil in the form of diesel fuel or kerosene. Hawaii generates about 70% of its electrical power using ship delivered diesel. The Caribbean Islands, many off-grid island communities off the New England coast of the USA, and small remote Alaskan communities use oil. There is little disagreement on burning oil for electricity though – but don't use it unless it is the only option.

For example, Monhegan Island is a small one-mile by a half-mile offshore Maine island with about 75 year-around residents. In the summer, it has about 700 persons, mostly tourists. It has a one-room schoolhouse that teaches K-12 to a dozen kids by a single teacher. It is an artist's paradise to walk the forests or paint the endless Atlantic Ocean as it pounds into the rocks (Fig. 1). There are several places to stay for the night and a small number of restaurants need power. It sits 10 miles off the Maine coast, and it does not have a submarine power cable from the mainland.

Monhegan Island is transparent on a short visit. You don't detect the power squeeze unless you notice that the hotel hangs its sheets to dry on a clothesline. You don't see that all food, water, and fuel must be brought on the small ferry from the mainland. Cooking is done with propane gas, and toilets are flushed with ocean water. But you do see that power cables are laid out on the ground from diesel generators to houses as you might string an extension cord in your living room.

Figure 1. A tourist hiking a Monhegan Island trail (photo by Elaine Hawkins).

How do they manage? They have three diesel generators providing 320 kW using about 135,000 gallons of diesel fuel at $43,000 per year. Residents pay a flat rate 72¢ per kilowatt-hour of power that is well above the 14.8¢ on the mainland. Residents are restricted to a maximum house current of 40 Amps that is much lower than the typical mainland 100 Amps. That means no electric dryers, ovens, or water heaters.

One solution is contentious. A proposal is in limbo to install a 2.5 MW nameplate wind generator 2.5-miles from the island. The island is near pristine give or take a few hundred summer tourists. It has a strong artist history, and these cultures and natural beauty bring out half of the residents in strong protests when their beautiful environment is threatened. A working wind system is targeted for 2020. An unsightly, noisy, nearby 2.5 MW wind generator is not on the to-do list. Welcome to a serious power problem. A thought sneaks in on the ferry ride back, that if the energy and population challenges on the mainland are not solved, Monhegan Island could be our electrical restrictive future.

The *New York Times* reported in July 2014 that most of the more than 200 small, isolated communities in Alaska rely on expensive diesel fuel to generate their power. Diesel generators are now their only reliable option. The villages burn a total of several hundred thousand gallons of diesel fuel per year at prices that approach $10 per gallon.

Oil Transportation on Rails –Bomb Trains

Oil transportation has a history of significant fatalities and accidents. Trucks, railroad, tank cars, and pipelines transport oil from the fracking fields, but railroad tank cars are the most common, and that is a problem. The shale oil fields aggravate the danger by their increasing rail transport, and much of that is crude oil. Crude oil is unprocessed oil pumped from the ground that contains volatile vapors such as methane, ethane, propane, butane, pentane, and hexane. Crude oil can ignite at lower temperatures causing large fireball explosions. Refined oil does not have this problem.

There have been severe accidents in oil transport, especially the July 2013 disaster in Lac Megantic, Canada (Figure 2). An unattended 63-car crude oil train was parked on an elevation while the engineer went to a hotel for the night. Unattended, the train had a brake failure and rolled down a slight downhill grade for seven miles into the town. It derailed in Lac Megantic on a curve at 65 mph with explosions incinerating 47 people and destroying a large portion of the small town [1,2].

This was not an isolated accident. The title of "bomb trains" has surfaced to refer to these explosive cargoes. The Lac Megantic story on the surface is simple that a dumb train engineer parked his train for the night on a hill seven miles from Lac Megantic. The root cause says something different. The real cause was a system that allowed the railroad industry to dictate the safety and reliability rules. Over the course of a few years, the industry fought to reduce labor costs and the manpower on a long freight train went from 7 to 5 to 2, and then to a single engineer driving the train. The caboose was removed. The Lac Megantic engineer was experienced and had been working for 18 hours which is six hours over the regulation [1,2].

Figure 2. The 63 car bomb train explosion in Lac Megantic, Canada in 2014 destroying the town center and. killing 47 persons. The fire lasted 3.5 days. (*Photo: Paul Chiasson | AP Canadian Press)*

The Sightline Institute posted photos of ten crude oil railroad explosions that occurred from June 2013 to July 2016 (Fig. 3) [3]. Crude oil train explosions are typically this violent. Much of the oil cars are old and not designed to handle the corrosive crude oil or contain explosions. The Hudson River Valley in New York sees 15-30 oil trains per week carrying crude oil products from the Bakken Play in North Dakota. Bomb trains move through Chicago on their way to the east coast of US and Canada. The rail industry claims that the rate of severe accidents is decreasing, but the number of oil trains is increasing correlating with more productivity in the Bakken oil shale fields.

Figure 3. Crude oil bomb train explosion on the Mississippi River in Galena, Illinois, March 6, 2015 (The Sightline Institute). This scene was replicated ten times across the country between 2013 and 2016.

Seattle has several crude oil trains per day traveling through the center of the city (Figure 4). These trains pass within 100 yards of the city's major league baseball, soccer, and football stadiums. Oil trains sometimes coincide with arrival or departure crowds.

Figure 4. Crude oil train snaking through downtown Seattle. (Marcus R. Donner/Puget Sound Business Journal)

The oil train explosive accidents are recent. This began about 2005 with the growing success of the Bakken play, so it is a relatively new problem. A recent oil train derailment occurred within Seattle, but there was no explosion. The

Bakken Shale dominantly produces oil some of which is shipped 1600 miles to the state of Washington and then to Pacific Coast terminals for shipping. Other trains go to the East coast.

Arctic Drilling

A storm-related beaching of the mammoth Shell Oil arctic exploratory rig called the Kulluk occurred in Alaska in 2012 (Figure 5) [4]. The Kulluk was intended to explore the Alaskan and Arctic Ocean regions for oil. It drilled five exploratory wells in the Chukchi Sea north of the Bering Strait before heading back to Seattle. The Kulluk rig never made it back. Storms caused it to lose control from its towboat and drift aground in the Aleutian Islands. The rig was later retrieved and sold for scrap in Asia. The magnitude of the Gulf of Mexico British Petroleum and the Alaskan Exon Valdez oil spills expose the additional risk of oil ocean drilling and transport in extreme environments. All these count when tallying the pluses and minuses of electricity generation.

US oil production peaked in 1979, and previous oil reserve depletions were given a reprieve bolstered by the same fracking technique that gas uses. However, oil fracking also has the same rapid decline in well production and temporary sweet spot characteristics that shale gas exhibits.

Oil is a non-sustainable fuel. The *New York Times* reported that Great Britain's North Sea oil fields have been depleting since 1999. The oil and gas production dropped from 7.6 to 6.1 billion pounds from 2011-12 to 2013-14. The huge Saudi Arabian Ghwar oil reservoir has produced since 1946. Saudi Aramco claims that it still contains about 70 billion barrels, but it is depleting [5]. The Permian Basin in Texas that was so plentiful in the 1930s and 1940s is still pumping oil. But it is depleting although recently reinvigorated by oil fracking. That is not a positive future.

While Hawaii and the Caribbean Islands are investing in renewable energies, but solar and wind cannot match the 24/7 dependability of oil or other traditional methods of electricity generation, such as coal usage. The renewables solar and wind can reduce oil consumption, but not replace it.

Figure 5. The exploratory oil drill rig Kulluk beached in Aleutian Islands by severe winter weather. The rig is 250 feet high, has a drill depth of 20,000 feet, and is not capable of motoring in the sea.

(https://response.restoration.noaa.gov/about/media/noaa-responds-shell-drilling-rig-kulluk-grounding-gulf-alaska.html)

In contrast to other energy sources, oil has little controversy. Most agree that oil is a poor choice to produce electricity, but it fills a niche that other sources cannot. Oil will probably maintain its current position in the USA as a source of energy for distant communities, and sometimes as a peak load generator supplement along with gas, solar, hydroelectric, and wind energy.

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Chapter 12

Nuclear Power I

No one really thought of fission before its discovery

Lise Meitner, 1938

A Tribute to Lise Meitner – She was the first to see fission

It may seem strange to begin the nuclear section writing about a woman that few have heard of. Many contributed to the methodical march of nuclear physics. But Lisa Meitner's nuclear fission analysis, Enrico Fermi's demonstration of a sustaining chain nuclear reaction four years later, and Albert Einstein mass-energy equivalence equation $E = mc^2$ rise above the rest. Meitner analyzed data from a German nuclear experiment in 1938 that she had designed and built, and she told the world that a nucleus has split and gave a calculation of the immense energy released [1,2]. The world physics community went viral with experiments.

Her story stands out as a brilliant Jewish woman's progression and later demise in the severe man's world of a dangerous Germany in the 10 years before the Second World War. Meitner worked alongside Europe's elite nuclear physicists; Bohr, Einstein, Currie, Heisenberg, Dirac, Gamow, Fermi, Planck, Pauli, Chadwick, Schrodinger, de Broglie, Landau, Born, and her famous doctoral advisor Ludwig Boltzmann. She was a quiet experimentalist who also understood the theoretical basis.

Nuclear power and its radioactivity knowledge didn't spring from a set of PowerPoint slides, but from the tedious and often dangerous work of physicists before and during the first 50 years of the 20^{th} century. Marie and Pierre Curie laboriously isolated radium as a pure source of radioactivity, Albert Einstein's $E = mc^2$ energy-mass equivalence, Ernest Rutherford's model of an atom with a nucleus and outer shell electrons, James Chadwick's discovery of neutrons, and Enrico Fermi's neutron research on the radioactivity of atoms, particularly uranium, thorium and plutonium, was achieved without computers but with relatively crude instruments and a lot of thought. The Curie's paid with their lives with premature deaths from non-protected ionizing radiation exposure to radium.

Nuclear excitement accelerated in the early-1930s, and Lise Meitner was in the center of it. Lise's obsession was mathematics and physics [2]. After a PhD from the University of Vienna in 1907, she went to Berlin where she stayed until 1938. In her first five years she was given a small basement room at the University of Berlin and told she could not go upstairs where the men worked. When she needed a toilet, she had to use a nearby restaurant. On top of that, her parents paid her low salary. In 1909 she attended a lecture by Einstein in which he derived $E = mc^2$. She used that knowledge 30 years later to help explain the theory of fission.

Then things began to improve for women in education. She moved to the prestigious Kaiser Wilhelm Institute near Berlin and teamed with Otto Hahn. He became a close friend and their scientific partnership went on until 1938. He was a radio-chemist and she was the physicist. She could guide, do the instrumentation, perform, and give a theoretical base to the research, and he could analyze the resulting material. But in the dark background, she was a Jew in Nazi Germany.

That team worked, and they became part of the elite scientific society in Europe [2]. Yet her name in Germany was not commonly mentioned among these giants. It is as if she wore camouflage. She always deferred first name recognition to Otto Hahn on the many papers she wrote with her friend even when she did the majority of work and thinking. She was a rare experimental hands-on scientist that could analyze the theory of what they did. Hahn worked his share but did not know the physics. She did not complain, but attention was on Hahn. She was sometimes referred to as his student, which may be the only thing that got under her skin. But outside of Germany, Lise was recognized by peers with the respected elite of Europe [2].

The Kaiser Wilhelm Institute then relaxed its policy toward discrimination against women, and eventually Lise rose from her demeaning status to the title of Professor with students, lab space, travel money to science gatherings, and a small salary. But the beginning of the end of her active 32-year career in nuclear physics began one day in 1933, when she and a friend listened to Adolf Hitler give his inaugural address as Chancellor of the German Reich. It was an ugly and surreal speech: a chancellor who made no secret of his contempt for democracy, science, and Jews [2]. Meitner survived the next five dangerous years in Berlin as a Jew somewhat buffeted by the Kaiser Wilhelm Institute and its director Max Planck.

But the net tightened to abolish all Jews from public or university positions. The Nazis wanted an all Aryan faculty. Her positions of professorial prominence, salary, and passport were taken from her. Many of her Jewish friends were arrested, and she was legally forbidden to leave Germany when her passport was taken. She was offered positions in countries outside Germany but couldn't get there. In the fall of 1938, she escaped through a small exit point to Holland with a personal bag and 10 marks of money.

She accepted a position at a Swedish Institute, and that is where she wrote her famous work on fission with her talented nephew Otto Frisch who had escaped to England in 1933 [3]. Otto Frisch was not a 20-year younger nephew pulled up by his more famous aunt, but an accomplished physicist. He was a Jew, and in 1933 he escaped to London from Germany. In 1940, he and Rudolph Peierls wrote a stunning paper on the design of an atom bomb. His words on the amount of enriched uranium required for an explosion were, "… To my amazement it was very much smaller than I had expected; it was not a matter of tons, but something like a pound or two. ..." The bomb project had been stalled, but this energized the project in a race with Nazi Germany. Frisch then accepted an invitation to join the American Manhattan Atomic Bomb Project in Los Alamos, New Mexico, and later spent his career at Cambridge University in England. Lise Meitner, Niels

Bohr, and Albert Einstein declined the invitation to join the Manhattan Project. Bohr stayed in Nazi occupied Denmark and was cited for getting 3,000 Jews safely to Sweden.

Now back to Sweden and the Otto Frisch collaboration with his aunt. Otto Hahn in Germany sent a paper in 1938 about an experiment that Lise had created about bombarding uranium with slow neutrons, but Hann couldn't understand why so much barium appeared in the result. Frisch told the story that Lisa and he were skiing in Sweden when the idea of a fractured nucleus occurred [3]. They sat on a log off the trail as Lise made notes. The strictly enforced rule in Germany was that an Aryan could not work with or publish with a Jew. As a minimum they would lose their job. So, Hahn and Lise were cutoff except for mail, but their relationship turned dark.

Hahn and his new partner Fritz Strassmann published the results of the experiment that Lise had proposed and constructed the equipment before she escaped Germany. Lise was not mentioned in the German paper. Uranium bombarded with neutrons showed a barium product that was a considerably smaller atom than uranium. This was the first experiment showing fission, but. Hahn couldn't explain it.

Meitner and nephew Frisch quickly explained Hahn's results in a separate short paper to *Nature* [2,3]. Uranium has an atomic number of 92 and barium has 56. If a split occurred, then there should be a missing element with an atomic number of 92 – 56 = 36 which is the atomic number of krypton. Frisch did an immediate experiment and found krypton. The numbers matched expectation that the uranium atom has split. Frisch coined the word *fission* from a biology analogy. Meitner and Frisch did further calculations including using $E = mc^2$ to account for a missing mass and calculate the energy released during fission. A small mass had converted to a large energy as Einstein had predicted, and the atomic bomb race was on against Nazi Germany.

The fission impact on the world nuclear community was instant as was a bitter reaction from Hahn. He spent the remainder of his life belittling her work and making false claims. His published words refuted his claim that he had discovered fission. The Berlin experiment created fission, but Hahn could not explain what he had done, and he owed much to Meitner and Frisch. In 1944 Otto Hahn won the Nobel Prize in Chemistry over objections from Niels Bohr (another Jew) and others. Meitner was not mentioned. All this is a bit weird since WWII was at its height. The world physics community knew the story, and Hahn was shunned from full recognition or invitation to future gatherings. But Nazi Germany used "renewable facts" to elevate Hahn, and even tried to explain that Einstein's Theory of Relativity was developed by Aryan Germans [2].

Lise Meitner's professional life ended as she spent the next 15 frustrating years at the Swedish scientific lab. It was a bad scientific match, and she moved to Cambridge in 1960 where she died in 1968. The point here is to honor a woman who was the "Mother of Fission" and the nuclear energy that we drive our generators with. Now let's look at the properties of these nuclear power generators.

Primer on Nuclear Reactions

Nuclear reactors have a severe public relations problem. A serious people problem is that for one to understand nuclear power one must understand nuclear reactions. That is not so easy. I took a nuclear physics course many years ago, and lately I worked hard to update my understanding. The popular criticism of nuclear power is mostly not true but understanding the real weaknesses of nuclear reactors require knowing how the whole thing works. If you cannot dig into the nuclear physics, then you must rely on someone you trust. If you are at a loss as to who to turn, I suggest listening to the nuclear physicists and nuclear engineers [4-12]. It is an important issue

I know that an intelligent person can have trouble understanding where nuclear should be headed, and that is central to the problem that nuclear reactors have with public acceptance. Coal, gas, and oil fuel are relatively simple, and don't have this understanding problem. Let's begin the nuclear journey and hope the writing style will help you through. Always keep in mind that if you cannot understand the essence of nuclear reactors, you may be reduced to talking points from a PowerPoint slide.

When you see a nuclear power plant, something seems missing. It doesn't have a smokestack. You do see white steam condensation coming from a cooling tower. That water condensate doesn't come from the nuclear reactor but from the exhaust end of the steam turbine that is physically isolated from the nuclear reactor. A nuclear reactor plant does emit miniscule amounts of radioactive gases, liquids, and direct radiation [3]. This radiation is harmless and is about one-third that of coal smokestack emissions. Within a 50-mile radius of the reactor, a person would receive a yearly dose of 10 micro rem, which is small compared to a natural background of 300 millirem per year from natural sources of radiation. Radioactive emissions from an operating nuclear power plant are virtually zero.

Nuclear power has a different personality than coal, gas, or oil. Organized opposition to nuclear power has been strong in Germany, Japan, America, and India. The opposition power was evident after the Fukushima-Daiichi accident in 2011. The leaders of Japan and Germany quickly announced that their countries would close all nuclear plants and replace that lost power with coal. These decisions were driven by the political will of the nuclear opposition groups, not by engineers, physicists, climate scientists, or public health workers.

The stakes are high since nuclear power is the only baseload power generation process that emits no greenhouse gases or deadly toxins. Despite opposition claims, modern nuclear power is clean, green, safe, and can reliably power large populations. But our current reactors use a submarine design done in the early 1950s, and it has weaknesses. It is time to move on from the older designs that use the explosively high-pressure steam that was a factor in the 3-Mile Island, Chernobyl, and Fukushima-Daiichi reactors explosions. It is also time get rid of our old design that generates 99% radioactive waste for 1% of uranium fuel consumed. And let us get rid of the notion that lower levels of radiation kill and produces mutant offspring –it doesn't as shown by Japanese data on 4th generation survivors of Hiroshima and Nagasaki.

Nuclear particles

The following simple sentence took about two dozen physicists and chemists almost 50 years to write [4-12]. *A nuclear reactor emits α, β, γ, and neutron* *particles and its fissioned daughter products from nuclear fuel.* Intense research took place in Europe (Denmark, Germany, England, France, and Italy), at McGill University in Canada, and in America from 1895 to 1938. The fight to understand objects they could not see, but could measure their effects with relatively crude instruments, is a wonder of human achievement. Natural uranium and thorium have weak random radioactive decays, but their isotopes and byproducts triggered by aiming fast or slow neutrons at them are not weak.

Transmuting is a modern word that grew out of the ancient 15^{th} century alchemy that tried to change one element in the periodic table to another, such as lead or mercury into gold or silver. Isaac Newton spent a few unsuccessful years of his career trying to solve the transmutation challenge. Elements are uniquely identified by their number of protons and by their atomic weight that is the sum of protons plus neutrons. If we could swap off these two numbers with another element we could transmute. Modern transmutation finally happened with nuclear reactions that remove or add protons and neutrons. Transmutation happens in nuclear reactions when uranium turns into plutonium, or when a large nucleus splits into smaller atoms. There is a reshuffling within the Periodic Table. What are these particles that are emitted when an element transmutes?

An *alpha particle* is a helium atom with both electrons removed, making it a double positive charged helium atom He^{++}. The α-particle is itself an atomic nucleus with two protons and two neutrons. A normal helium atom has a nucleus of two positive charged protons, two uncharged neutrons, and two negative charged electrons in an outer shell surrounding the nucleus. Overall helium is electrically neutral, but the α-particle is a double positive charge with its two electrons stripped.

The atomic number is the number of positive protons, and the atomic weight is the sum of the number of protons and the number of neutrons in the nucleus. Helium has an atomic number of two (protons) and an atomic weight of four (2-protons plus 2-neutrons). The atomic number and atomic weight determine an element's behavior and physical properties. Normally the positively charged protons are balanced by the negatively outer shell charged electrons.

An α-particle can be blocked with a sheet of paper, human skin, or a short distance in air, but can cause biological cell damage if ingested or inhaled. While not externally so threatening to humans, α-emission is important when it exits a uranium or thorium nucleus and reduces their atomic number by two and atomic weights by four. This is called alchemy or transmutation.

α-particles eject from a uranium nucleus at about 5% of the speed of light. That would be 9300 miles per second, or 33.5 million miles per hour that is certainly worth a celestial speeding ticket.

β-particles have two forms. They are either negatively charged electrons, or positively charged electrons called positrons. The symbols are β^- and β^+. β^- particles are ionizing particles, and as such, can cause cancer in biological cells. β-particles are also used in cancer therapy when they are focused on a specific location. A few mm of aluminum can block β-particles.

We should not dismiss β-radiation as simply a fast electron emitted from the nucleus. It is more complicated because when an electron leaves the nucleus, a neutron converts to a proton. Thus, the atomic number increases by one, but the weight doesn't change. When a positron ejects from the nucleus, a proton transforms to a neutron. It is a strange behavior at the foundation of when an atom changes places in the Periodic Table, but you share with the scientific giants that no one knows why. It just is.

Gamma rays are high-energy electromagnetic radiation with high frequency and short wavelengths. They are high-energy photons with a short wavelength of about 10^{-12} m. The wavelength of a γ–ray is less than the diameter of an atomic nucleus. γ–rays are similar to X–rays but are more powerful and biologically hazardous. Don't stress if these three sentences are a mystery, but we had to inject a physics description of what we are dealing with. Just remember that γ–rays are bad if you are exposed to them for extended periods at higher radiation. But the gamma radiation equipment in a hospital is a daily treatment to destroy cancer cells. Aluminum, concrete, water, and soil are effective as gamma ray shields. Lead has a higher density and is a slightly better shield. Effective lead thickness for shielding varies from a fraction of an inch to a foot depending upon the γ–ray energy.

A *neutron* has the same small mass as a proton, but it has no charge. It is a unique and useful property that a neutron particle stream does not deflect in an electric or magnetic field. So, a neutron is the only particle that can enter the space of an atom and not be repelled or attracted by the positive proton nucleus or by the negative outer shell electrons. So, when we want to trigger a nuclear reaction, the neutron is the perfect particle to tickle a particle from an already slightly unstable uranium nucleus. Different nuclear designs specify either slow or fast-moving neutrons to trigger a chain fission reaction. So, neutrons are both an emitted radioactive particle and a subsequent bullet to cause a nucleus to transmute or fission. Neutrons slow when passing through water or carbon graphite. Whereas electrons are the fundamental particle in explaining electronics, neutrons take on that role in nuclear chemistry.

The whole business of fast and slow neutron effects on large atoms was intensely studied in the 1930s and somewhat concluded when Enrico Fermi won a Nobel Prize in 1938 for firing fast and slow neutrons at most of the elements in the Periodic Table. Slow and fast neutrons are essential to discussion of nuclear reactions. Why would a slow neutron be preferable than a fast, higher energy neutron? A slow neutron doesn't directly split an atom, but it is more easily absorbed by the large nucleus if it is going slow. That extra neutron hanging on to a nucleus makes the nucleus unstable and particle emission happens. Slow neutron absorption could be characterized by the phrase "The straw that broke the camel's back." A fast-moving neutron "smashes" the nucleus into pieces. Fast and slow are designed into two different types of nuclear reactors.

Are you confused at this point? If so, go back and try to get an image of *α, β, γ,* and neutron particles. The large, heavy elements like uranium, thorium, and plutonium get rid of or acquire these particles and go radioactive. So, it is essential that you struggle to get the images in your brain.

Two Ways to Capture Energy of Nuclear Particles

A fissile element such as thorium-232 naturally decays through ten transitions ending at lead-208. This chain is naturally occurring, and an energy particle is emitted at each transition. The problem as you must have guessed is the half-life. The thorium first transition to radon-228 has a half-life of 141 billion years. Enough of this.

We can save 141 billion years by simply firing slow neutrons onto the thorium nucleus. We get fission radiation instead of a decay chain particle radiation. Both approaches emit alpha, beta, gamma, and neutron radiation particles.

Nuclear Properties

Paul Dirac wrote that we can see the physics of Isaac Newton dealing with planets in motion, but nuclear is different [1]. The esoteric physics of quantum mechanics that can analyze and predict nuclear behavior must be taken on faith. But importantly there is nothing in atomic theory that is analogous to seeing planets whirl around the Sun. Electrons are somewhere in the outer shell, but not whirling around like planets.

Scientists can generate a radioactive particle stream and observe how the stream reacts to the polarity of applied electric and magnetic fields. This property identified positive α-particles and negative or positive electron β-particles, and no effect on γ-ray and neutron direction. Another tool was to observe how different materials and thickness could differentially block these particles. Thus, with great mental intensity and labor, a model of the nuclear atom was slowly born. Modern nuclear reactors stand on the shoulders of those giants who carved the theory. Early Nobel prizes went to those people.

The atoms that concern us in current nuclear reactors are uranium, plutonium, their isotopes, and daughter atoms. These large atoms can split and transmute into smaller strongly radioactive daughter atoms such as isotopes of iodine, cesium, strontium, barium, radon, radium, krypton, and potassium. These radioactive elements keep transmuting down a chain of elements until they land on lead which is not radioactive. These elements comprise most of the nasty waste from reactors. Inhaling small particles places them deep in the lungs where these heavy atoms can be fatal. Fortunately, all nuclear reactors have a thick concrete and steel containment cover that protects the environment from steam explosions or unintended release of these nasty radioactive elements.

When uranium (U) ore is taken from the ground, there are actually two uranium's of interest [4,5]. They have the same atomic number (number of protons) but differ by three neutrons in their nucleus (three neutron mass units). Elements with the same number of protons (atomic number) but different number of neutrons are called *isotopes*. ^{235}U has an atomic weight of 235 while ^{238}U has three more neutrons and an atomic weight of 238. Both isotopes of uranium have the same atomic number of 92. Just remember that these differences in atomic weight have huge differences in nuclear reactions. There are two major differences besides the atomic weight. ^{235}U is only 0.7% of the uranium ore extracted from the earth, and ^{238}U has 99.3%. This (0.7% / 99.3%) ore composition is called *natural uranium*.

The second profound difference is in radioactive half-life. The half-life is the amount of time it takes for the radioactivity rate to decay to half its value. ^{235}U is radioactive with a half-life of 710 million years, while ^{238}U is barely radioactive with a half-life decay of 4.3 billion years, and ^{238}U is considered stable. The longer the half-life, the lower the radioactivity. Yes, it can be said that some atomic waste will decay over billions of years, but importantly their radioactivity is so slow that it is not a hazard even if you hold it in your hands. ^{235}U will fission if slow neutrons are absorbed into its nucleus. Uranium is a heavy toxic metal that if inhaled is a health hazard that is dangerous during mining if precautions aren't taken.

The ^{235}U isotope is the only naturally occurring fissile atom, and it can decay into smaller radioactive atoms. When we say that uranium is radioactive, we refer to the 0.7% ^{235}U. A nuclear chain reaction is sustained with an isotope mix of ^{235}U, ^{238}U, and ^{233}U. But in the mix ^{235}U must be enriched to 3% - 5% to sustain a chain reaction.

It is relevant that an atomic bomb requires more than 90% ^{235}U enrichment to explode. This makes it difficult for terrorists to build a uranium bomb and makes it impossible for a nuclear reactor plant with 3.5% ^{235}U enrichment to explode like a bomb. An easier route to bomb making is through plutonium-239 (^{239}Pu) that is a decay product of a uranium reactor. Fast neutrons ejected from the reactor process converts ^{238}U into ^{239}Pu in a chain of reactions. This allows a reactor method to create ^{239}Pu avoiding the more complex physical-chemical natural uranium enrichment methods used for nuclear weapons. α-particles are the most common radiation from Pu reactions. The transmutation of ^{238}U to ^{239}Pu defines a breeder reactor that create more fuel than they consume. This is discussed later.

Modern Nuclear Reactor History – Weinberg and Rickover

Two men in the 1940's set the course of nuclear reactors for the next 70 years. Alvin Weinberg and Hymen Rickover shared the history of reactor development as no others, but an unfortunate competition grew that to this day hinders full development of nuclear energy [13-14]. Weinberg joined the Oak Ridge National Lab (ORNL) in 1945 and remained at ONRL working on different reactor designs. Weinberg became the ORNL Director and oversaw the development of a variety of reactor designs until his death in 2006.

ONRL had a contract in the 1950s to deliver a nuclear-powered airplane engine that mandated a small, lightweight design. The idea stemmed from the 1940s to build a plane that could stay airborne for years regardless that no one would want to do that. Prototype engines were built, but the concept was flawed, and Weinberg and his physicists knew it. Airplanes must be relatively lightweight, while airborne nuclear reactors are heavy from the concrete and lead shielding. The development of airborne refueling brought a total stop to the project. But importantly the contract allowed ONRL to explore a variety of nuclear reactor designs.

Weinberg estimated that there are about 1,000 ways to design a reactor, but because of the long lead time to bring a reactor to prototype, it was important to choose carefully. Weinberg's approach was to see the wide range of nuclear designs, and he promoted diversity. But this submarine and aero military nuclear history feeds into the modern commercial nuclear reactor status.

In 1946, Weinberg patented the use of high-pressure steam temperature to increase electric generator turbine efficiency that is still the basis of the modern Light Water and Boiling Water Reactors that dominate the market (LWR, BWR). Weinberg taught and advised Rickover in the mid 1940s to more narrowly focus submarine power on the uranium Light Water high-pressure reactor. The Boiling water Reactor BWR burns raw uranium ore, requires deuterium, and runs at a lower turbine temperature. The LWR has about 75% of the market, so we will use LWRs as the point of discussion.

One of the Weinberg designs that was field tested seemed the perfect choice. The design used the element *thorium* fuel instead of *uranium.* Thorium radioactive research goes back to the 1920s and later in the 1940s. The novel ONRL design dissolved thorium in a molten liquid salt that can operate at atmospheric pressure at high temperature. The thorium reactor was tested for five years in the ORNL Lab and then tested from 1977-1982 at the Shippingport nuclear commercial plant in Pennsylvania. Thorium reactors are about 99% more fuel efficient, much safer than uranium high temperature steam reactors, and they safely passed different induced failure modes.

The thorium reactor operating with liquid fuel at atmospheric pressure eliminated the high-pressure steam explosion problem that later plagued two of the three LWR most serious uranium reactor accidents. The thorium waste was only 1% contrasted with 99% waste for uranium. And thorium ore was so minimally radioactive that it could be safely mined, and this heavy metal was used for jewelry. Thorium competed with uranium in the 1940s but lost as uranium reactors generated plutonium that made an easier path to build nuclear weapons. The perfect reactor design didn’t make it, and thorium reactors and Weinberg were pushed aside in a blunt political move for the uranium design.

Hyman Rickover was a Naval Academy graduate in the 1920s. He later earned a master’s degree in Electrical Engineering from Columbia University and entered the submarine service before WWII. He was aggressive, belligerent, and insensitive to the naval ranks above and below him. Time Magazine described him in 1954 as:

“Sharp-tongued Hyman Rickover spurred his men to exhaustion, ripped through red tape, drove contractors into rages. He went on making enemies, but by the end of the war he had won the rank of captain. Rickover was assigned to work with General Electric on nuclear propulsion for destroyers. He locked in and learned everything he could about nuclear energy and chemistry. He then led the rapid development of the first nuclear submarine, the Nautilus in 1954 [15]. The Nautilus was a miracle submarine able to operate submerged for up to three months and travel underwater at 25 knots. It used Weinberg's uranium Light Water Reactor (LWR) design that later was fitted into aircraft carriers and cruisers. The first Nautilus reactor generated a relatively low 10 MW of power. Modern naval reactors generate 100 MW – 250 MW. Rickover's submarine design principles were simplicity, reliability, and safety. The Nautilus made Rickover the most powerful person in nuclear reactor designs (Fig. 1). He won a reputation as a man *who gets things done.*"

Figure 1. The *Nautilus* submarine. The 10 MW nuclear reactor design was an LWR; a design that dominates world reactor designs today. The *Nautilus* was launched in 1954 and set records for speed (25 knots), underwater submersion (2 months), and diving under the Arctic Ice Cap [14].

Rickover's achievements were monumental. He faced challenges in 1951 on a nuclear power plant for a submarine that were: (Wikipedia)

- In the early 1950s, a megawatt-scale nuclear reactor would take up an area roughly the size of a city block.
- The prototype for the USS *Nautilus* propulsion plant was the world's first high-temperature steam nuclear reactor.
- The basic physics data needed for the reactor design were as yet unavailable.
- The reactor design methods had yet to be developed.
- There were no available engineering data on the performance of water-exposed metals that were simultaneously experiencing high temperatures, high pressures, and multi-spectral radiation levels.
- No steam propulsion plant had ever been designed for use in the widely varying sea temperatures and pressures experienced by the condenser during submarine operations.
- Components from difficult, exotic materials, such as zirconium and hafnium, would have to be extracted and manufactured with precision via techniques that were as yet unknown.

President Eisenhower ordered Rickover to make a reactor for land-based power, and in 1956 Rickover delivered one to the Shippingport, Pennsylvania commercial plant on the Ohio River. The first US commercial nuclear plant used a nuclear reactor intended for a cancelled aircraft carrier. The Shippingport project took 2.5 years. That is in contrast to the modern 10-20 years to install a modern nuclear reactor.

Rickover was appointed head of the Atomic Energy Commission (AEC), and later he critically used that power to suffocate the thorium design developed at ORNL. Uranium reactors had a military advantage over thorium since the uranium reactor bred plutonium (Pu) for atomic weapons. A breeder reactor for Pu avoided the complex and costly chemical and physical uranium enrichment methods. And Rickover had a personal identity in his mega achievement with uranium LWRs.

When the political wars were over, Rickover sat as head of the AEC, and Weinberg was removed as Director of the ORNL for opposing the research direction of nuclear reactors [13,14]. Thorium reactors were killed and LWRs were in. Today, the thorium reactor design is finally getting some traction in the world to replace the many design flaws of the LWR and the BWR.

Thirty-three countries now use nuclear energy for electrical power generation. The World Nuclear Organization reported in December of 2014 that there were 437 commercial reactors, 70 under construction, and 179 ordered. These numbers change each year as some nuclear reactors come online, and some are decommissioned. Nuclear energy generates about 2,359 Gigawatt*hours of total world power, and most of the nuclear growth is outside the USA. Nuclear powered electricity will be with us for some time, but it may take different reactor forms.

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Chapter 13

Nuclear Power II

A physicist once observed that those who know the most about nuclear reactors fear it the least, while those who know the least about nuclear power fear it the most.

Tribute to Enrico Fermi – He Showed That a Controllable Chain Reaction Was Real

Errico Fermi and Lise Meitner were similar in scientific achievement, but different. He was out going, and she was inward. She scraped for every inch of educational opportunity, and he was a recognized prodigy from early age and pulled up by the system. Both were modest. Fermi did many things including experiments on the essential role of neutrons in nuclear reactions [1]. He won the Nobel Prize in Physics for that work in 1938. His wife Laura was a Jew, and they immigrated to America from Fascist Italy on the same week that he won the Nobel Prize. He was the face of Italian world respect in science, but Lisa had a different situation in Germany. Meitner and Fermi were in frequent communication with their latest results. Her most noteworthy work in the 1930s was identifying fission, and his was neutron chemistry that supported the theory of the first nuclear chain reaction that he directed.

A nuclear chain reaction was conceived in 1933 when Leo Szilard considered how a chain reaction bomb would work, and he patented a device in England for an atomic explosion [1]. Szilard said that the idea came to him as he waited for a traffic light to let him cross a London street. Fermi directed the team that would demonstrate a controllable nuclear chain reaction. On December 2, 1942, 40 people gathered at the University of Chicago football stadium in a squash court under the west side stands. It was an unusual place for this momentous experiment, but it was big enough to hold the large equipment and be out of sight. It was here that Fermi led the experiment showing the chain reaction using natural (un-enriched) uranium. It was to be held at the Argonne Forest Lab south of Chicago that was under construction, but a labor strike forced the switch. They were aware that it was not humorous that the experiment was now so close to downtown Chicago.

However, the football stadium has some nuclear humor in its history that is worth telling. In the 1920s and most of the 1930s, Chicago was a premier college football university. When Robert Hutchins became University President, he later banned football in 1938. Chicago has a pure academic reputation. One alumnus put it," The University of Chicago is the place where that weird kid from your high school went to college." Hutchins said removing football was easier when the last two years of the program were so terrible. The last game was an 85-0 defeat by The University of Michigan. Football was banned the next month. Years later against student wishes, football was reinstated. "Ban the Ball" protests weren't enough, but this prestigious university may hold title to the most unusual school cheers. Those who are drawn to this book may appreciate one cheer that goes

Logarithm, biorhythm,
Entropy, kinetics,
MPC, GNP, bioenergetics!
Maximize and integrate,
Titrate and Equilibrate–
GO, MAROONS!

Now back to beneath the west side stands at the football stadium and the nuclear chain reactor experiment. It took a month and a half to assemble the large blocks of carbon graphite that surrounded the reaction. Cadmium is a neutron grabbing atom that can suffocate the reaction when it is in the path of neutron particles. Cadmium was wrapped around wooden rods and inserted into the nuclear pile. The rods were pulled up and down to control the radioactivity. Pull up and the reaction increases; push down and the reaction decreases. The experiment was a success, and a chain reaction was confirmed. Fermi in his cool manner even broke the group for lunch early in the experiment.

Fermi led this gigantic experiment developed by the greatest scientific minds gathered from Europe and the United States [2]. Although invited, Albert Einstein and Lise Meitner declined to join the American Manhattan Atomic Project. The Fermi experiment date on December 2, 1942 is important since the subsequent atomic explosion in New Mexico occurred only two years and nine months later on July 15, 1945. It was an incredible achievement particularly in such a short time. The technical problems were immense, but the financial backing and brain power were also immense.

Properties of Nuclear Power

The uranium nuclear position within the four baseload generators is complex. Nuclear reactors emit no greenhouse gases and relatively low greenhouse gases in the mining and transportation of uranium [3,4]. A nuclear plant emits minute traces of radioactive gas. But that amount is about one third of the radioactivity emitted by coal exhaust stacks for the same power generation, and about 100 times less radiation than coal waste slag. A truck delivers nuclear plant replacement reactor fuel rods every 18-24 months compared to long daily coal trains or continuous leaky natural gas pipelines.

No one has died from a nuclear power reactor in the US since its introduction over 65 years ago [5]. Nor have there been elevated cancer rates among nuclear workers or surrounding region populations. It appears to be the perfect electrical power generating plant. With this incredible record, why the public outcry against its use?

Public perception is a major reason, and it has been up and down. Concerns are about fear of nuclear radiation, public safety, disposal of waste material, terrorist theft of nuclear waste, long-term reliability, cancer, biological mutation, and startup and repair costs. Fear is the driver on this list [5,6]. Let’s look at the data on these properties and the origins of the public fear of nuclear power.

The Growth of Nuclear Fear

Nuclear fear grew with a sequence of events that began with twice Nobel Prize winner Marie Curie and her husband Pierre Curie's exposure to pure radium in the 1890s. Both died premature deaths from strong radiation. Next was the severe radiation poisoning of the radium watch assembly women in New Jersey in 1917-1938 [7], then to the atomic and hydrogen bombs in the 1940s and 1950s, the American-Russian cold war, the Three-Mile Island Pennsylvania accident in 1978, the Chernobyl nuclear accident in 1986, and the Japanese Fukushima Daiichi tsunami disaster in 2011 [2,8].

These major incidents still retard the modern development of nuclear power. Fear is unique to nuclear reactors since coal, gas, and oil driven power don't raise fear despite serious death, injury, illness, and greenhouse emissions. This must stop! No one has died in the over 65 years that military and commercial nuclear reactors have operated in the United States!

Marie and Pierre Curie spent much of their professional life handling radium; an element that is about three million times more radioactive than uranium. They often carried samples of pure radium in their lab coat pockets. Marie died at the age of 68 of presumed radiation poisoning (anemia). Her husband Pierre died years earlier and was debilitated by severe radiation poisoning. He had begun to physically decline, and his university teaching load was reduced. Pierre died in a street accident when he stumbled and fell and was run over by a street trolley. Pierre shared a Nobel Prize with Marie in1903, and she won it alone in 1911 since the Nobel Prize rules are that it can't go to a dead person.

Radium was responsible for the premature deaths of the Curies. Radium has 33 isotopes, and all are radioactive [7]. Radon is an isotope that is gaseous and is a threat in buildings and homes especially if near sources of radon such as the Rocky Mountains. The Curies had no knowledge of the radioactive health danger to higher dosage.

Next, the United Sates Radium Corp. watch company in Orange, New Jersey in 1917 used young women to paint radium on watch dials with small camel hairbrushes so the dials would glow in the dark [7]. The radium girls dipped their fine brushes in a radium liquid and then lip twisted the brush to a fine point in their mouth. Small amounts of radium were ingested from the radium solution that built up over a few years' time and permanently deposited in bone marrow. The radium liquid was not concentrated but over a few years, the radium in their saliva was ingested and built up in their bones.

The jawbone was closest to the saliva and an early symptom was that their teeth fell out and jaw bones fell out in pieces [7]. The face and other parts of the body became grotesque for these young women some as young as 13. A disinformation campaign by the company included accusing the women of syphilis. A repeat of this New Jersey scenario was played out in Ottawa, Illinois beginning in 1922. A famous lawsuit was filed in 1926 by five of the women, and the Radium˜ Dial Company was found guilty of hiding the dangers. Modern US occupational public health laws derive from this case.

The Curies died premature deaths from working close to radium for years without shielding protection. Little was known about radiation at that time. The radium girls died from ingesting radium. It took years, but finally the radiation prevailed, and the deaths were slow and agonizing. These are valuable lessons.

The instant devastation of the two atomic bombs dropped on Hiroshima and Nagasaki, Japan in 1945 was unnerving (Fig. 1) [2]. Approximately 80,000 people were killed in each bombing with about 85% from the thermal blast and the shock wave. Radiation killed 15% of the victims all of whom were within a mile from the explosion. One survivor described the bomb explosion as if one moment you saw a metal object falling in the sky. If just before the explosion you closed your eyes and opened them five seconds later, you would see that many square miles were leveled.

These data on the radiation effects on a large population gave a better understanding of the effects of extreme nuclear radiation and power. Radiation fallout from atom bomb testing after WWII, particularly of cesium-137 and strontium-90, was a warning of the risk of uncontrolled radiation. The public mood was changing.

How do we understand these radiation horror stories against our current nuclear reactors? First, recognize that these lethal examples were caused by high radiation doses close to the atomic bomb explosion or accumulation of radium with high radiation dosage to workers and surrounding regions. However, there is much consistent evidence of low dose radiation that cause no increase in cancer rate. But the nuclear reactor waste has high ionizing radiation, is dangerous, and is shielded from human contact.

Figure 1. The aftermath of the Hiroshima atom bomb. The bomb exploded about a third of a mile above the ground. The survivors and descendants have been medically tracked for over 70 years, and they remain the strongest data on the effects of flash radiation. Despite low level radiation, no increased cancer rates were found for those persons more than a mile from the blast [2].

Two Big Nuclear Reactor Accidents

Three-Mile Island: The Three-Mile Island nuclear meltdown accident in 1979 near Harrisburg, Pennsylvania dramatically impacted the American public (Fig. 2) [8]. Two weeks prior to the accident, a movie called “The China Syndrome¨

was released with actors Jane Fonda and Jack Lemmon. The fictional movie described a nuclear power plant meltdown in California due to faulty quality control during construction and confusion by the operators when a core melt was happening. As fate would have it, the Three-Mile Island nuclear accident two weeks after the movie opened had virtually the same failure scenario. That was too much for public consumption, and the anti-nuclear fever began in earnest. Those groups such as the Sierra Club and Green Peace International that had actively campaigned for years against atomic weapons found a new cause - the commercial nuclear reactor [8].

Figure 2. The 3-mile Island nuclear plant on the Susquehanna River in Pennsylvania. Unit-2 was destroyed and is missing from the upper left region.

Several points emerged later. The first was that no one was killed or suffered subsequent radiation illness at Three-Mile Island or its surroundings. The second point was that the safety containment structure placed over the reactor held as designed. The average increase in surrounding region radiation was less than 1% of normal. The last point was that even though a small amount of radioactivity gas was released to the environment, abundant subsequent studies in the area showed no increase in cancer rates of the population. The damaged Unit-2 reactor was sealed and not used again.

Fukushima-Daiichi: The disaster at Fukushima-Daiichi in 2011 was the third major world nuclear accident. Water cooling pumps lost power, so the fuel rods continued to heat up. Hydrogen gas came from the fuel rod cladding at very high temperature and exploded. The prevailing wind blew much of the emitted radionuclides out to sea, but a smaller amount of radiation hit the ground to the west and south to Tokyo. The elevated radiation level in Tokyo was still lower than normal background values in Denver.

Robert Gale is an MD with a PhD in physics. His medical career specialty is radiation health treatment [9]. He treated patients on-site at Chernobyl and Fukushima-Daiichi. Gale with Russian physicians treated the workers at Chernobyl with methods not yet readily available. Intense radiation attacks bone marrow disrupting the production of red and white blood cells (RBC, WBC). Victims die of anemia or become susceptible to diseases that cannot be fought off by low white cell counts. Modern treatment is to transfuse blood to increase RBC and to inject a synthetic hormone into the bone marrow to stimulate WBC production. This treatment is not 100% assured [9]. Gale later mentioned that the number of radiation victims requesting medical help at Chernobyl swamped the ability of the medical staff to treat them.

The Fukushima disaster workers were monitored for radiation, and not allowed to exceed health limits. No one has died from radiation at Fukushima-Daiichi, but the mechanical force of the tsunami killed about 20,000 people in the area. These deaths had nothing to do with the nuclear plant, but it did little to reduce the fear of the general world population. Two workers were drowned when they were trapped in a flooded room. It became a popular false rumor that the 20,000 deaths were caused by nuclear radiation, not the tsunami. Japan, Germany, and Italy closed down many of their nuclear reactors.

Cumulative Reactor Years

Figure 5 shows a plot of the rising number of nuclear reactor-years that have accumulated for 50 years, and the years of the three major accidents. One reactor-year is one reactor operating for one year. The data show a total of 174000 reactor years with deaths occurring only at Chernobyl. While these deaths were horrific, our judgement on the nuclear reactors should not be influenced by that gross Chernobyl negligence. The Three-Mile Island and the Fukushima accidents produced zero radiation fatalities after a cumulative 60 reactor years.

[https://www.forbes.com/sites/startswithabang/2020/10/21/the-world-needs-nuclear-power-and-we-shouldnt-be-afraid-of-it/?sh=406097016576]

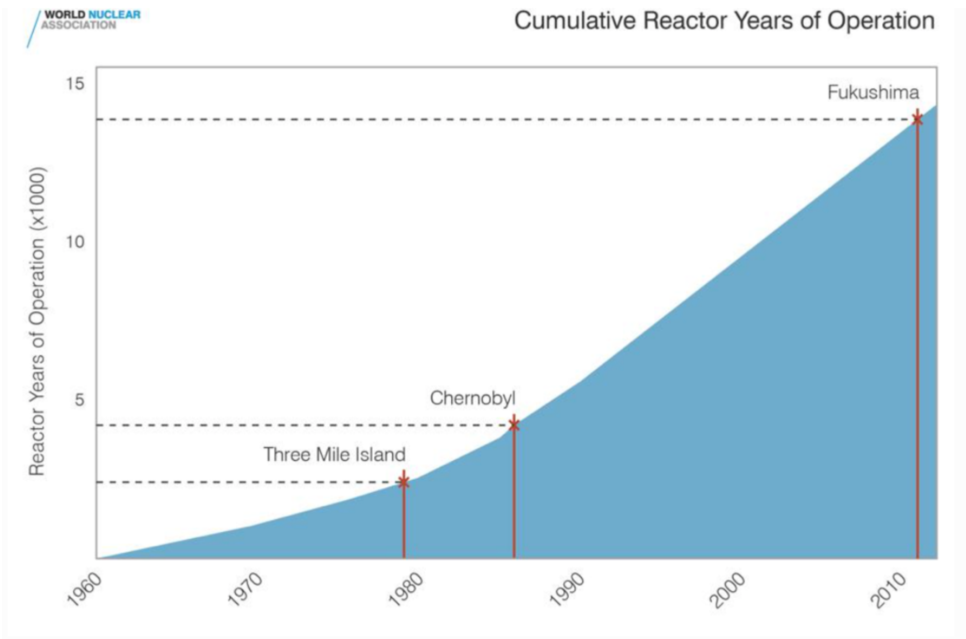

Figure 5. Reactor operational years since 1960.

Models that Predict Nuclear Radiation Induced Cancer

Reports, such as from Greenpeace International, project tens of thousands of premature deaths using the linear no-threshold model (LNT) at low dose. There are no data to support this [9-11]. The atomic bomb and Chernobyl data showed that a person has about a 50% chance of dying from cancer if subjected to a 10 Sv (Sv = Sievert) or greater dose of radiation. We can put this single 50% - 10 Sv point on a graph (Fig. 6) of leukemia cancer fatality risk due to radiation versus the dose absorbed by a human. And if we draw a straight line from this 50% dose fatal point to the zero-origin point, we can erroneously predict death rates for any dose on this straight line. This is the Linear No Threshold dose-response model (LNT), and it is used to enact more stringent and costly radiation regulations on nuclear plants.

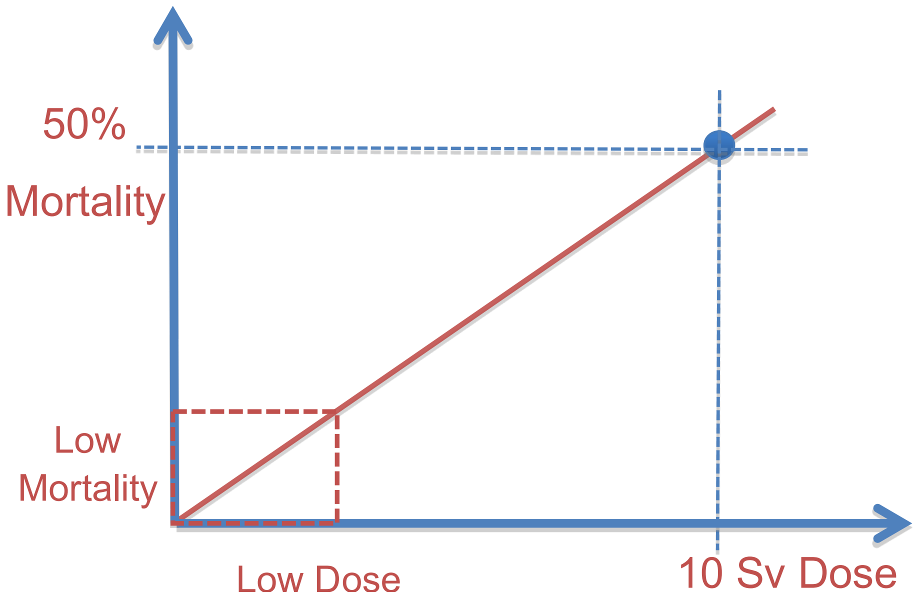

Figure 6 A mortality-dose graph illustrating the LNT model. Pick a rate point at a high dose, draw a straight line to zero, and assume that the mortality data correlate in the low dose range. This is not true, and it has important ramifications for the financial impact of setting standards.

Suppose a human low dose was a low 4 mSv and the population was 50 million. The LNT model would predict that over a lifetime, 10,000 persons above the normal rate would contract cancer. Numbers like this have never been seen, but the LNT model is still used by the government and by opponents of nuclear energy. It is a cautious, conservative approach. These numbers generate fear by predicting wildly unrealistic numbers of fatalities. This is an extremely important property as we examine the low-level radiation levels that humans are subjected to everyday and assess data on fatalities. We will now look at evidence for low or nonexistent death rates at low dose that contradicts the LNT model.

While the LNT model sounds reasonable, the low dose model does not correlate with the zero low cancer rate increases found in low dose environments. Nuclear reactor commercial and naval personnel, those who work in medical radioactivity, and those who live in natural higher radiation environments do not show elevated cancer rates contrary to predictions of the low-dose model [9-15]. The LNT model is based on the wrong assumption that if a single radiation particle strikes the human body, a cancer will result. The body does not work that way.

Evidence will be shown that cancer rates may actually *decrease* in a low dose environment [10,13,14]. This is the counter intuitive *hormetic effect* that is the science-based evidence that shows healthier growth in most plants and animals under low doses of some toxins, poisons, and radiation. The effect is similar to an inoculation response that injects low levels of a disease substance followed by a body resistance to that disease. That is also counter intuitive to get healthier by injecting a disease in your body, but it happens.

Does low-level radiation inoculate against the cancer observed at high doses? It seems to, but we don't know the details. Current theory suggests that a recovery mechanism can handle low dose radiation, but that mechanism becomes swamped when dose rates get higher. Biologic cells do contain a mechanism for low dose radiation gene repair that can be saturated at higher doses, and this is support evidence for hormesis [14].

> *The Nobel Prize in Chemistry 2015 was awarded to* ***Tomas Lindahl, Paul Modrich*** *and* ***Aziz Sancar*** *for having mapped, at a molecular level, how cells repair damaged DNA and safeguard the genetic information.*
> The Royal Swedish Academy of Sciences [14]

The study found that thousands of DNA molecules in a cell are mutated per day. But a repair mechanism exists for those damaged DNA molecules [14]. If the radiation dose is low the DNA can be repaired. As the dose increase, the repair system is swamped, and more damaged DNA can't be repaired.

Hormetic research indicates that the human body is not a passive accumulator of radiation damage, but it can actively repair damage caused via several different processes. This scientific issue is important. The LNT model is wrong but is used to set tight nuclear regulation that forced huge extra costs, engineering challenges, construction delays that are needlessly imposed. Imposing near zero radiation limits on nuclear reactors drives the startup cost and lengthens construction time. And most importantly it can scare the public into believing things that are not true.

Most government agencies say no to hormesis. But the 2005 French Academy of Sciences-National Academy of Medicine and others take an opposing view concerning the effects of low-level radiation. It rejects the LNT as a scientific model of carcinogenic risk at low doses.

"*Using LNT to estimate the carcinogenic effect at doses of less than 20 mSv is <u>not</u> justified in the light of current radiobiological knowledge*."

"...its (hormesis) existence in the laboratory is beyond question, and its mechanism of action appears well understood"

Radiation hormesis stands in stark contrast to the linear no-threshold model (LNT). The LNT model implies that even if a single radioactive particle strikes a person, then a cancer can result — false. The French Academy considers that the LNT model is only useful for simplifying the administrative regulatory task.

The data from people in Hiroshima who survived the atomic bombings have been extensively examined (Figure 7). A recent report plotted the number of leukemia victims at Hiroshima as measured against the calculated radiation dose at a distance from the bomb. Those data were presented in a table in 1957, and an important relation was not recognized. The plot shows the clear *J*-shape of hormesis. The *J*-shape supports the cell repair data [13]. Doses from 0 to about

100 rem showed not only no increase in leukemia rate, but a cancer rate decrease compared to the normal rate. The conversion is 1 Sv = 100 rem.

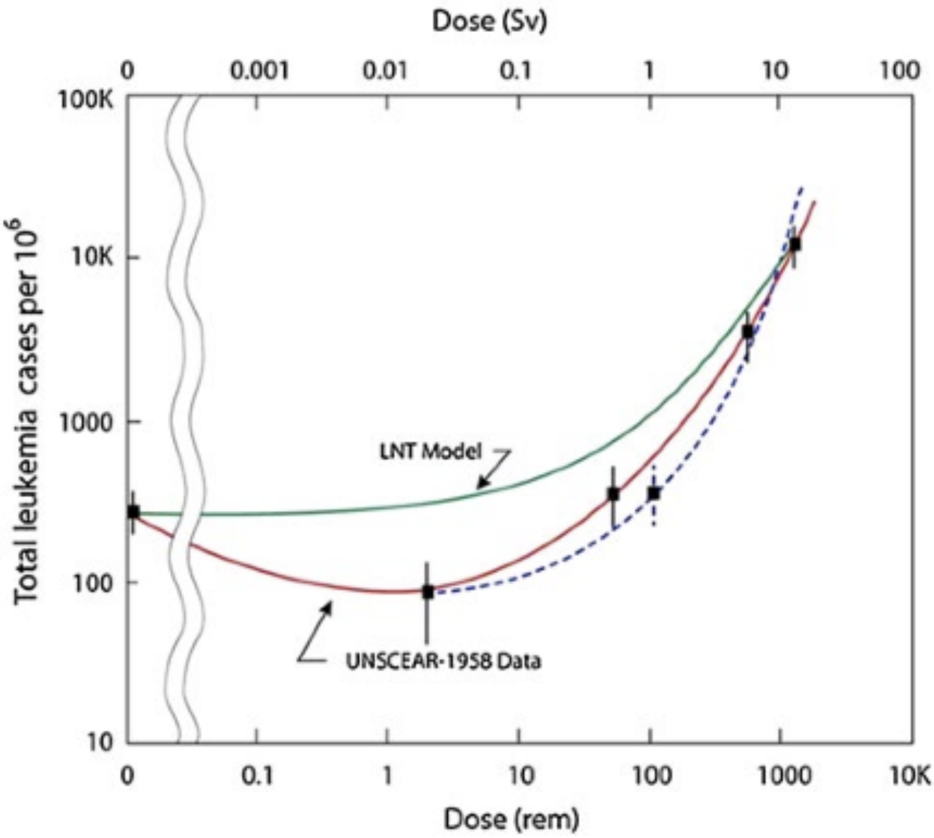

Figure 7. Leukemia incidence in the Hiroshima survivors. Data taken from 1950–1957. Data from Jerry M. Cuttler, "Leukemia incidence of 96,000 Hiroshima atomic bomb survivors is compelling evidence that the LNT model is wrong," Arch. Toxicol., Letter To the Editor, Feb 7, 2014 [13].

The data from people who survived the atomic bombings have been extensively examined (Figure 7). A recent report plotted the number of leukemia victims at Hiroshima as measured against the calculated radiation dose at a distance from the bomb. Those data were given in a table in 1957, and an important relation was not recognized. Those data were plotted, and the plot shows the clear *J*-shape of hormesis. The *J*-shape supports the cell repair data [13]. Doses from 0 to about 100 rem showed not only no increase in leukemia rate, but a cancer rate decrease compared to the normal rate. The conversion is 1 Sv = 100 rem.

Look at Fig. 7 again and understand the profound impact countering the emotion of nuclear reactor fear. Richard Steeves has an MD and PhD in physics. His presentation at the TEAC7 in 2015 reviewed the data on radiation hormesis adding lung-fluoroscopic data that showed the J-shape of hormesis. Breast cancer rate was lower at low dose radiation [17]. Steeves also observed that radiologists don't have a higher incidence of cancer.

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Chapter 14

Nuclear Power III

The Chernobyl Reactor Disaster

Chernobyl: Chernobyl is a 1200-year-old village that became a nuclear reactor site producing power in the Ukraine region of the Soviet Union in the 1980s. The Chernobyl nuclear accident in April 1986 was monumentally bad [1,2]. This section will detail the failure since it is important to understand the many mistakes in bringing a bad light water reactor design online. That is the significance of a closeup examination of Chernobyl. Chernobyl scared people and with good reason. We will conclude that it was a confluence of the worst human organization, illogical judgement, and bad design. But today Chernobyl cannot be used to influence our important decisions on nuclear baseloads!

This chapter goes into detail to provide insight into how a nuclear reactor design and implementation were so horribly screwed up. The Chernobyl reactor should be considered as only half constructed when it went online. The extremely important protection structure was ditched in favor of a light structure that saved the Russians half of their budget and allowed online delivery 2-years earlier - a costly decision. If these details are not in your comfort zone, then skip to the end of this section and read the final review paragraph. But the Chernobyl explosion is invaluable in putting our current study of nuclear options in perspective.

There were four nuclear reactors at Chernobyl in the early 1980s with a fifth under construction when the accident happened. The Chernobyl accident was more than a nightmare, and it warrants a detailed examination. The Merriam - Webster Dictionary defines accident as "an unfortunate event resulting especially from carelessness or ignorance." Chernobyl perfectly fits this definition.

Superficial explanations for the Chernobyl reactor explosion with its damage to the Western Ukraine and Northern Europe were that the reactor had a feeble explosion containment cover (true) and that safety features in the design were turned off to run a reactor shutdown test (true). But these two facts may be only 20% of the causes of the failure, as the root cause had to do with people and their organizational structure and the engineering design itself. There are two exceptional books on Chernobyl.

Serhii Plokhy is a historian and author who was born and educated in Russia. He is a professor of Russian history who accepted a Directorship at Harvard University in 2007. His book *Chernobyl: The History of a Nuclear Catastrophe* was published in 2018 [2]. Plokhy's unique insights are his ability to review copious documents and papers in Russian and his interviews of many persons in their native language. Plokhy also brings the discipline of a professional historian as he describes the political atmosphere in Russia in the 1980s as Russia battled to reverse a drooping economy.

Adam Higginbotham is an experienced investigative writer and in his well-researched book, *Midnight in Chernobyl*, he covers the same ground as Plokhy with different eyes [3]. He gives a somewhat deeper feeling for the human horror, and it was horrible. My review uses both descriptions. They should be read to grasp how bad a nuclear disaster can be. People who fear nuclear power may point to Chernobyl but understanding will allow a decision that Chernobyl cannot be used as a club to impede nuclear power sources.

The energy stakes were high in the 1980s, and Russia's recent success in nuclear power generation made the nuclear power source central to moving a lagging manufacturing economy. Mikhail Gorbachev served as the last general secretary of the Communist Party of the Soviet Union (1985–91) as well as the last president of the Soviet Union (1990–91). He drove the nuclear power direction from the top. Those charged with a rapid development of nuclear power were under extreme deadline pressures from politicians and upper-level managers. The upper-level people did not understand nuclear power generators, and only looked at power delivered, deadlines, and cost. Safety was assumed and not a priority. Deadlines were fixed and failure to meet them would cost the victim his reputation and who was then often fired.

Public knowledge was that Russia had not experienced a serious nuclear accident at this point (not true). A serious near melt down happened to an LWR in 1975 at Leningrad., but an emergency shut down prevented an explosion. The failure mode at Leningrad was identical to the one 11-years later at Chernobyl, and the lessons at Leningrad were not remembered. There was a design flaw that the reactor operated unstable when at low power levels. Other serious nuclear accidents occurred in the Soviet Union [3].

If the upper leadership of Russia believed that it never had a serious accident, then what better way to meet deadlines and save money then to sidestep safety features. By eliminating the secure containment structure, the delivery time of a nuclear plant could be reduced by two-years, and costs may be cut in half. And operator training was minimized.

Construction managers who failed to meet a deadline were fired even when the failure was traced to inability of suppliers to even deliver their products on time to the site. The same pressure was put on suppliers who then shipped product with less concern for quality. One study found 700 defects in a material shipment. Site managers fudged their construction status reports. Work was done in this suffocating atmosphere, and herein was a serious and uncorrected problem.

The popular Russian light water reactor named the RBMK was a graphite-moderated nuclear power reactor designed and built by the Soviet Union. Initially it had several dangerous flaws especially one that under certain conditions it would stimulate a runaway power condition. The technical term for one of this is "High Positive Void Coefficient." It happened when water in the coolant became overheated and generated steam. Water is intended to slow the reaction by absorbing neutrons, but steam absorbs fewer neutrons. Steam allowed an abnormally high neutron concentration that freed up more neutrons to latch onto the U^{235} atoms increasing reactor mutations. This can dangerously increase the reactor power. This was one fundamental problem with the RBMK reactor, and the Leningrad problem reappeared at Chernobyl. It happened when during tests, the power levels of Unit-4 were reduced below the full power for which the reactor was designed. The RMBK was unstable at low power mode.

Why was this reactor shut down experiment needed? There is an emergency procedure called a SCRAM, where in an emergency the reactor must immediately shout down, and an operator literally presses a SCRAM button. There was a serious time lag problem during a SCRAM. When a SCRAM caused an instant shut down, there was a 45 second delay in the RBMK before emergency power could activate the reactor coolant backup pumps. These coolant pumps kept the fuel rods from overheating and melting.

Why was there a 45 second delay? It took about that long for the motor driven control rods to descend into the reactor core and slow the reaction when an emergency SRAM was initiated [2]. The 45 second delay was a safety problem. An idea was to test if during this 45 second delay, power from the inertia of the rotating reactor turbine could power the coolant pumps. The test had the risk that the reactor might go out of control, and that the test required disabling of all components to simulate a real shut down. Some risks were known, and others weren't, but a decision was to hope that it would be safe.

There were ominous signs in the test as the output power was reduced from 1 GW to 500 MW to 200 MW. At lower output power, the reactor acted strangely not responding to the control rods. Inserting control rods should slow the reactor, but it didn't, it increased the reaction. The SCRAM signal activated twice but was ignored. The RBMK was designed for stable operation at full power and lowering the power level this far was into unknown territory.

Another important poor design feature were the 4,000 panel indicators. Operators received conflicting indicators, resulting in not knowing what was really happening in the reactor. The reactor operators normally would have chosen to terminate the test, but the pressure from higher management to complete the test was too strong to not go forward. Plokhy describes second by second reactor details over the last minute before two massive explosions occurred. The core melted, and the abundant graphite overheated and exploded through the flimsy protection structure into highly radioactive small chunks along with radioactive products. One Russian engineer described Chernobyl as a disaster waiting to happen [1].

The Chernobyl Explosion and Firemen Response

Two huge explosions occurred within seconds surrounded by earthquake strength vibrations. The reactor operators were not trained to handle a reactor explosion, and their reflexes were to look toward the steam turbine or part of the cooling system. The second blast blew off the feeble containment structure. The graphite particles were lethal to firemen who were near to or picked them up. A second blast shot fire up from the ruins of the reactor. Figure **3** shows the powerful devastation of the Unit-4 reactor.

Figure 3. The remains of Chernobyl reactor number-4, from the roof of the third reactor. Photograph: Igor Kostin/Corbis

Firemen at their station a mile away saw flames coming from the reactor. They saw a fireball. To them, it was a fire. It was a lethal distinction for the firemen. They had not been trained to deal with a radioactive nuclear reactor explosion, and they rapidly drove their trucks to the "fire" and were there within 5-minutes.

One team went to the roof of Unit-3 next to Unit-4. They fought a fire while walking in a molten roofing material mess of radioactive elements and graphite of various size. Graphite pieces were spontaneously catching fire. When the firemen returned to the ground 20-minutes later, they showed serious symptoms of radioactive poisoning. Another team went to the roof of the turbine hall and suffered the same fate. The symptoms were excruciating headache, nausea, slurring speech, vomiting, swollen dark brown faces, swollen lips and tongue, speech impediment, confusion, and guilt. They were driven to a hospital that took time to diagnose the unanticipated radiation poisoning. 29-persons died within minutes, hours, or days of radiation poisoning. When a convening committee wanted to talk to the reactor operators, they found that all were in the hospital.

The fire was extinguished about 5-hours after it started. But that did not stop the radiation. Water pumped into the reactor core became radioactive. Ionizing radiation came from decay products that were hurled into the atmosphere. Radioactive isotopes of iodine-131, cesium-137, and xenon-132 were in the mix as well as pieces of highly radioactive graphite.

About 11 AM the adjacent city of Pripyat became a topic when the radiation level rose to 1000 times normal [2,3]. Pripyat is an old village about 2-miles north of the Chernobyl reactors. Pripyat grew to 50,000 people who lived normal lives supporting the four reactors. Should a mass evacuation of Pripyat be imposed? Discussions went on for 36-hours. Misleading reports of radiation levels were given, with administrators reluctant to evoke the word evacuation.

The evacuation caution was “Don’t produce mass hysteria” or “You know what will happen if you make a wrong decision.” The decision was to pass on to a higher manager until that decision reached the Kremlin. The further a person was from Pripyat, the less knowledge and experience about radiation and nuclear energy. Unfortunately, this is where the Soviet system delivered the big and small decisions.

At 9 PM about 15 hours after the initial fire was extinguished, the reactor belched out three more explosions caused by the rapid natural half-life decay of xenon-133 that was reduced to a level that it no longer suffocated the uranium reaction. It happened almost exactly when the Soviet physicists predicted. Some physicists pleaded that Pripyat be evacuated because it was not certain that further explosions would not occur. Meetings and indecision went on for hours, until at 8 PM on the day of the explosion an order was given to evacuate Pripyat (Figure 4).

At 2 PM the next day, 1200 buses and 240 trucks began the Pripyat evacuation. Buses and trucks were irradiated as were the clothes and people who boarded. No one lives in Pripyat now, although a web site claims that one person lives there (Fig. 4). Wild animals have moved in, and that Pripyat is a ghost town.

Figure 4. The cold abandoned silent city of Pripyat. (from Google Maps)

An initial exclusion zone of 10 km was enacted affecting 12,000 people. Radiation levels later extended this to 30 km surrounding the Chernobyl reactor meltdown. Prevailing winds let a radioactive cloud drift to the west over western Ukraine to Belarus, Lithuania, Sweden, Finland, Scotland, and Denmark. The diameter of the radioactive cloud was estimated at 600 km. After 3-days, the Soviet government admitted what the western world knew, a massive radiation leak of products and radioactive graphite had occurred.

About 6,000 thyroid cancer cases were detected among children who drank milk with radioactive iodine. 15 children later died from thyroid cancer [4]. Thyroid cancer is not pleasant, but it is mostly treatable. If natural iodine pills are taken prior to radioactive exposure to saturate the thyroid, then the risk is greatly reduced from isotopic iodine. The thyroid gland is an iodine sponge whether the iodine is an isotope or not. The half-life of iodine-131 is 8 days, so after six weeks radioactive iodine absorption was no longer a threat.

The radiation dose impacted victim survival. The radiation physicians used the modern dose absorption unit of 'grays" where 1-gray equals 1,000 rems. Radiation attacks bone marrow reducing red and white blood cell counts, and patients die of anemia or vulnerability to disease normally fought off by the white cells. Dose absorption for each patient was estimated from blood tests and symptoms. Statistical estimates of dose and survival were

If dose greater than 10 grays, then certain death

If dose between 1-10 grays, some survival (numbers not given)

If dose between 2.2 –4.6 grays, one survival of 20 patients

If dose between 0.8 –2.1 grays, then ***all survived***

The last two low dose numbers give support to the radiation hormesis survival data from Hiroshima, the US 3-mile Island, the Denver paradox, and others. A low dose of radiation is not fatal. Even at higher doses, there were survivors, and in the 237 radiated people who were flown to Moscow, 187 survived. High ionizing doses are lethal or cause serious illness. But at the low non- ionizing radiation, the data are consistent – no adverse long-term effects.

Higginbotham writes that "One rem is a little less than the citizens of Denver, Colorado absorb from natural background radiation in the course of a year; 5 rem is the annual exposure limit for US nuclear workers; 100 rem is the threshold of acute radiation syndrome; and an instantaneous dose of 500 rem to the whole body would be lethal to most people [3]."

Plokhy reports that [2]

- 2-persons died immediately with the explosion
- 29-people died of radiation poisoning within the first 4-months.
- 237-people were airlifted to Moscow where 50 people died, and 134 showed acute radiation symptoms.
- A total of 6,000-children in Russia, Ukraine, and Belarus contracted thyroid cancer with 15 of these later dying.

The government pressured engineers to achieve low cost and short time to market that overrode concerns about its safety. The cheap cover saved money and shortened time to bring the RBMK-1000 online, but a strong containment structure system that was standard practice would have stopped the massive release of radioactive particles. The reactor had many flaws, and a significant one was the weak containment barriers over the reactor and the reactor building.

Other flaws were [1]

Dynamic instability with respect to power and steam perturbation

Discrepancy between the design parameters and actual operation

No training of operators or preparation if a disaster occurred

No emergency or warning signals from design

Operators not told of known dangers of a number of reactor characteristics

An International Nuclear Safety Advisory Group report identified 45 safety issues: 19 were high severity, 24 were medium severity, and 2 were low severity

- To recap, the explosion occurred during a test of how the reactor would respond if all power were shut down. How long would the latent heat of the nuclear pile continue to drive the generators? The safety backups were dangerously turned off during the test. The fuel rods lost cooling and a meltdown, explosion, and hydrogen fire occurred. Brave workers entered extreme areas to contain the damage without radiation monitoring. Most thought they were fighting a fire and were unaware of the extreme radiation that hit them [1,2,3].

Without a containment structure, radiated graphite chunks, radioactive cesium, strontium, and iodine escaped into the atmosphere and were brought to the ground by rain. The strontium-90, iodine-131, and cesium-137 are intensely radioactive.

The nuclear operators were blamed in the Russian investigations, but a later review showed that they were not given information or training up to the task. The time pressure, faulty design, and lack of adherence to the safety regulations used by the rest of the world was the cause. The operators had no part of these decisions. The International Nuclear Safety Advisory Group report wrote a profound point that "… nuclear plant designs must be, as far as possible, invulnerable to operator error …"

The world has used nuclear power generators since 1954. Nuclear power plant radiation has sickened or killed no one other than at Chernobyl. Nuclear reactors emit no greenhouse gases or toxins, and no other baseload source can make those claims. The Chernobyl disaster was unique and should have no influence on our future nuclear reactor decisions. Again, the initial RBMK-1000 should never have been deployed. Later models corrected the flaw and some RBMK units still operate today.

The 40-year Chernobyl Lethal Cleanup Operation

A second Chernobyl event was the subsequent death and sickness from the massive radiation cleanup [1]. Cleanup workers were given little to no training in cleaning a radiation environment of the contaminated buildings, equipment, animals, vegetation, and soil. The cleanup crews were called liquidators and eventually numbered 600,000 workers over a 30-year period who weren't trained in radioactivity cleanup.

The unresolved question is how many liquidators died a premature death over several years from strong radiation induced sickness. There were spots of high radiation such as when untrained liquidators picked up fragments of radioactive graphite. This and certain areas exposed the workers to lethal high radiation doses. There were exposures to dust with radioactive strontium, cesium, and plutonium that a strong containment structure would have prevented. The identity of who was exposed to how much radiation and where they relocated after the exposure will never be known. It remains a dark cloud over Chernobyl. But many more persons died than the 28 disaster workers at the Chernobyl reactor plant. It is estimated that hundreds of thousands of the cleanup workers may have died early deaths. Many were exposed to low dose radiation, and they survived, but no information exists for those persons

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Chapter 15

Nuclear Power IV

If the atom were the size of a bus, the size of the nucleus would be the size of a dot above the letter "i"

- Otto Frisch

Images of the Atom

An atom's volume is the sum of its nucleus and the electron cloud surrounding the nucleus. Now for the mind boggle described by Otto Frisch [1]. Imagine that the size of an atom was as big as a large auditorium. The atomic nucleus would then be the size of the tip of a sharp pencil. That is impressive but also consider that the nuclear energy in our reactors (or bomb) comes from that tiny dot. A uranium dot contains 92 protons and 146 neutrons, and they are really small. We can only dwell in wonder over what is not intuitive, but it is real. Thank you to the scientific giants who pried into the dot to expose its secrets.

Fear and The Human Radiation Paradoxes

Human evolution took place in a sea of radiation, and we still remain surrounded by natural nuclear radiation. Estimates of hundreds of thousands of premature deaths attributed to low dose nuclear radiation are not substantiated, but fear is deep in a large segment of the population [2,3]. Let us look at some of the everyday nuclear low-level radiation paradoxes that we accept in contrast to the fear associated with a nuclear reactor.

The oceans contain uranium, and we swim in them. Sunbathers lie lightly clothed on a beach under that great nuclear fusion furnace 94 million miles away and under the background cosmos radiation, and not think much of it (Fig. 1). The Sun emits a wide spectrum of electromagnetic radiation and particles, and cosmic space radiates charged particles and gamma rays. Bananas have measurable amounts of radioactive potassium and we eat bananas.

Figure 1. Sun and cosmic bathers in Rio de Janeiro playing in nuclear radiation.

The Earth's atmosphere and magnetic field give us partial protection against incoming charged particles from space, but not 100% protection especially in the polar latitudes where the magnetic field dips into the Earth. Sun damage to the skin may be removed as skin cancers such as lethal melanomas typically appearing later in life. A small amount of solar radiation is essential for producing Vitamin D.

We are exposed to low levels of radiation when we fly. The radiation above 35,000 feet altitude is mostly ultraviolet from the sun and cosmic particles from deep space that travel through the aircraft. But the Center for Disease Control (CDC) writes that you would be exposed to about 0.035 mSv (3.5 mrem) of cosmic radiation if you were to fly within the United States from the east coast to the west coast. This low level of radiation is less than the amount of radiation we receive from one chest x-ray https://www.cdc.gov/nceh/radiation/air_travel.html

Electronic memories can upset at these altitudes from low dose cosmic particles. The cosmic and solar radiation at these altitudes is different from that of a nuclear reactor but does illustrate that the public can ignore radiation.

Nuclear technicians and engineers spend a great deal of time around nuclear reactors. Naval personal who operate the shipboard nuclear power plants have amassed over 6200 reactor-years, the total reactor years in the US is over 14,000 reactor-years. No elevation in normal cancer rates is found for persons who work near the reactors. No one has died from radiation from a commercial or military nuclear reactor in the United States since the first naval reactor fired up in 1954. Notice that we use the phrase cancer rates. Importantly, a normal control rate of cancer from the population must be established before declaring whether the low-level radiation increased or decreased the cancer rate.

Natural High Background Radiation Locations

Every location on Earth has natural radiation with average annual doses between 2 and 4 mSv [5]. Many locations in the world have natural radiation levels more than 100 times higher, and they are called high natural background radiation regions (HNBR). We will mention three of these regions and the paradox that cancer rates are not elevated.

The Denver Paradox contrasts Denver's 50% higher background radiation levels than other cities such as New York. Denver has a natural radiation dose of about 0.9 rem per year, and New York City has a 0.6 rem dose. Denver lies in a granite rock environment rich in radium, radon gas, and uranium. Uranium decays to radium and then to gaseous radon and its many radioactive short half-life daughters. The subsequent radiation is mostly α and β particles that are especially dangerous when inhaled deep in the lungs. The higher one-mile Denver altitude reduces the protective atmospheric cover and slightly increases the solar and comic radiation. A 50% higher radiation level than some large cities, and a lower cancer rate defines the Denver paradox.

Ramser, Iran has a radon radiation level that is 40 times higher than New York City [5]. Ramser is one of the highest natural radiation sites in the world and is fueled by nine converging rivers heavy in radium. Cancer incidence is not higher in Ramser than lower radiation cities. Preliminary studies indicate it may be lower.

Kerala, India has a natural background radiation that emits about 8 micro Sieverts per hour of gamma radiation, 80 times the dose rate equivalent in London. A study of 69,985 residents published in Health Physics in 2009 showed no excess cancer risk from exposure to this terrestrial gamma radiation.

A hypothesis is that these anomalies are due to hormesis and the underlying DNA repair mechanism of cells. But the significance is the public fear of anything with the words “nuclear” and “radiation.” A consequence is that radioactive emission standards may be overly strict on nuclear reactors leading to higher costs, delays in construction, and comparison of nuclear risk is inflated when compared to coal or natural gas.

The normal cancer rate in the Chernobyl pre-radiated area was 7/1,000, and the post-accident rate was 10/1,000. Robert Gale observed there are two accurate observations [6]. We could say that the cancer rate increased 43% or we could say it only increased by only three persons per thousand. Both are accurate numbers, but a writer can skew the impression depending on choice. Much of the local Chernobyl radiation was high dose from the escaped nuclear waste. The Fukushima-Daiichi data are recent, and life follow-up studies are too early. Our low dose data do not predict an increase in the normal incidence of cancer. Again, the radiation level in Tokyo was elevated after the tsunami, but it was still lower than Denver.

Genetic Mutation and Birth Defects

Genetic mutation implies that DNA was damaged from nuclear radiation, and that the mutation was passed to the next generations. With the exceptions of breast and colorectal cancer, cancers are typically not a genetic disease, and these important exceptions are not found to increase over normal levels after nuclear radiation exposure. Data from surviving victims of the Hiroshima and Nagasaki atomic bombs have been extensively studied with no trace of genetic mutation in themselves or in their children or grandchildren.

An Exclusion Region was set up following the Chernobyl explosion in which all persons were evacuated. The region is about twice the size of Rhode Island and a diversity of wild animals moved in and mixed with those animals that survived the disaster. The low-level radiation region became a wildlife sanctuary (Fig. 2). The animals included bears, moose, deer, lynx, wolves, otters, beavers, and horses. The animals reproduced with indications that offspring are healthy, although autopsies showed slightly elevated radioactivity in some internal organs. Contrary to rumor and some web sites, there has been no sightings of 2-headed animals or any genetic aberrations. But genetic mutations to mammals remain a fear for some.

A wolf in the Chernobyl exclusion zone

Figure 2. A health wolf living in the radiated exclusion zone of Chernobyl. (From Laura Helmuth, Slate's science and health editor, www.slate.com)

Early after the Chernobyl disaster, some trees were stunted, and others lost their chlorophyll and turned red. Extreme aberrations occurred early in plants in their natural recovery period, but not in animals. However, some insects in lab experiments showed mutations under low dose environments. Scientific American reported in January 2015 that swallows in the exclusion zone of Chernobyl showed a decrease in population, decrease in life span, and genetic mutations. If true, this is an exception to properties found in other exclusion zone animals, but is it related to low dose radioactivity exposure? Do some insects not have the radiation protection of mammals?

What about birth defects from exposure to nuclear radiation? Most birth defects are not inheritable, although pregnant mothers exposed to alcohol, tobacco, mercury, lead, syphilis, or rubella can activate birth defects. In the US, 3% of normal children have one or more birth defects. And 2% - 7% show latent birth defects. This averages to 5% - 10% of all children as a normal rate of birth defects. This is a high normal birth defect rate, and it affects the accuracy of attributing small increases or decreases due to nuclear radiation [7].

Several studies were done on the effect of low dose radiation on the offspring of pregnant women [8]. The Mayak Nuclear Facility in Russia developed basic nuclear reactors, and it is where several studies were performed. Between 1948 – 1988, 8,466 children of 8,000 female workers at the plant were tested for cancers. The offspring child death rate was the same as the general population. A study reported in 2017 of about 11,000 female workers and residents along the Techa River in Russia where nuclear waste had been dumped showed no link between utero exposure and risk for hematological cancer and solid cancer incidence. An analysis of the offspring of female workers and residents near the Techa River showed a decreased solid cancer incidence and mortality rate among about 16,000 people.

An interesting observation is the link of genetic mutation to human evolution. Human evolution requires genetic changes that are favorable to survival and are passed to subsequent generations. Cosmic, solar, and natural earth radiations are the major sources of human DNA changes. So, does the low dose reactor radiation create cell physiologic changes in imitation of other natural DNA damages?

Our evolution was in a natural radiation environment, so did those who survived have a genetic advantage? Maybe so, but we don't know. The hormetic effect data suggest that DNA can undergo repair, and low dose exposed persons develop more tolerance to cancer [9]. This may be a genetic survival response to low dose nuclear radiation.

Light Water Nuclear Reactors (LWR) and Explosions

About 75% of nuclear reactors in the world are LWRs that use high-pressurized steam to transfer heat to the turbine generators. LWRs use uranium fuel rods surrounded by water that is circulated in the reactor core. Water moderates (slows down) the neutrons and also acts as the primary coolant of the fuel rods. If the water coolant temperature control is compromised, then the fuel rods can melt overheating the pressurized water causing violent steam explosions.

Steam turbine efficiency increases with temperature difference across the blades of the turbine, so a goal is to drive the steam turbine temperature as high as possible and the secondary exhaust temperature as low as possible. Water boils at $100^{o}C$ at normal atmospheric temperature, and this is a low temperature to drive a steam turbine. The LWR uses the Alvin Weinberg trick by raising the turbine input water pressure to over 150 atmospheres. This raises the boiling point to about $315^{o}C$ or 588 Kelvin and the turbine efficiency goes up. Some commercial generators now can go as high as $585^{o}C$. Cooling and condensing the turbine exit steam with water markedly lowers the exhaust temperature and pressure that further increases efficiency. That turbine backend trick goes back to the early days of steam engines. We should note that creating this high-pressure steam takes energy from the total reactor efficiency.

But the dangerous part of the LWR design is the high-pressure and temperature of the turbine section [10]. Explosions derive from the high-pressure water as in the 3-Mile Island and Chernobyl reactor when the core melted down. When water no longer covers the fuel rods, the core melts with enormous heat. The Fukushima Daiichi reactor produced hydrogen from the fuel cladding at highly elevated core temperature and it exploded. Reactor containment is designed specifically to contain the explosion of steam or hydrogen gas. This design essential was missing from Chernobyl.

Nuclear LWR Cost Issues

LWR nuclear plant construction is complex and expensive. The issues are construction of the physical plant, adherence to often changing federal safety regulations, operating costs that include nuclear waste disposal, military style security, fuel price, interest payments on loans, cost overruns, risk analysis, reliability, construction delays, and the need to compete with other electrical generation technologies. The upfront LWR costs ranged from $13 billion to $22 billion projected for the cancelled Duke Energy plant in Levy County, Florida in 2012.

There is not yet a uniform price for nuclear power plants, since they come from different generator companies, power capabilities, and designs. Nuclear operating costs are lower than coal, and nuclear eliminates the expensive scrubbers and cumbersome fuel transportation system of railroad coal shipping or gas pipelines. Nuclear plants do not emit greenhouse gases or toxic chemicals, thus eliminating the medical and environmental costs of coal or gas. That is a big deal, because an economic analysis includes all factors. Nuclear doesn't look so bad when all factors are considered.

Bernard Cohen described one impediment that drove up costs [11]. The cost of a nuclear plant escalates as construction time increases. The interest on the massive loans continues when there is no income. Delays allow inflation to work against profits. One delay was the escalating safety features demanded from evolving federal regulations. These may have been justified in designs 35 years ago. The Shoreham nuclear plant on Long Island was delayed by three years from "interveners" who disrupted the construction permit procedures with often irrelevant legal objections. The Seabrook Plant in New Hampshire was delayed for two years by similar tactics. The loan payments continue during the construction down time.

There is not a clean statement on nuclear costs compared to other techniques. If the cost of public health and environmental damage were included in coal and gas emissions, then nuclear is competitive. Government subsidies differ according to the technology. Nuclear is funded by a factor of 6.4 greater than coal, and wind and solar are subsidized at about a factor of 15 over nuclear.

A conclusion is that LWR nuclear reactor startup costs are higher than other base load generators. But if public health and other peripheral damages are included, they are not.

LWR Nuclear Waste

Gas and oil electric generators burn near 100% of their fuel, while LWR nuclear reactors use only about 1% of the fuel loaded in the reactor. The other 99% is transformed in the reaction into a highly radioactive mass, and it is removed and stored as radioactive waste. This 99% waste material was not radioactive prior to the reactor's fission. Nuclear fuel rods eventually clog up with non-fissile atoms such as xenon that poison the reaction, and then you must refuel.

The decaying fuel rods contain ^{238}U, ^{235}U, ^{239}Pu, and many daughter decay fragments that are radioactive, such as barium, strontium, cesium, iodine, krypton, and xenon. High-speed neutron collisions convert ^{238}U to ^{239}Pu. Fission product atoms have a statistical distribution of the daughter fragments. When a single uranium atom fissions, it splits into two daughter atoms with the sum of their atomic atom numbers equal to that of the parent atom that fissioned.

The US policy is to store the nuclear waste on site in a cooling tank for five years until radioactivity cools and then find a more secure and permanent site, which currently does not exist (Fig. 3). Depleted fuel rods are removed and placed in a water tank to cool. The rods are stored in highly secure containers, where the lids are welded to the container, and put in indefinite storage. The casks are heavy from lead lining used as a radiation shield, and because uranium is about the heaviest of the elements. Most cask storage is now kept at the plant site, despite risks from flooding or terror attack. The casks are designed to withstand extreme physical conditions. The issue is a strong political force where citizens do not want a large nuclear storage facility in their state.

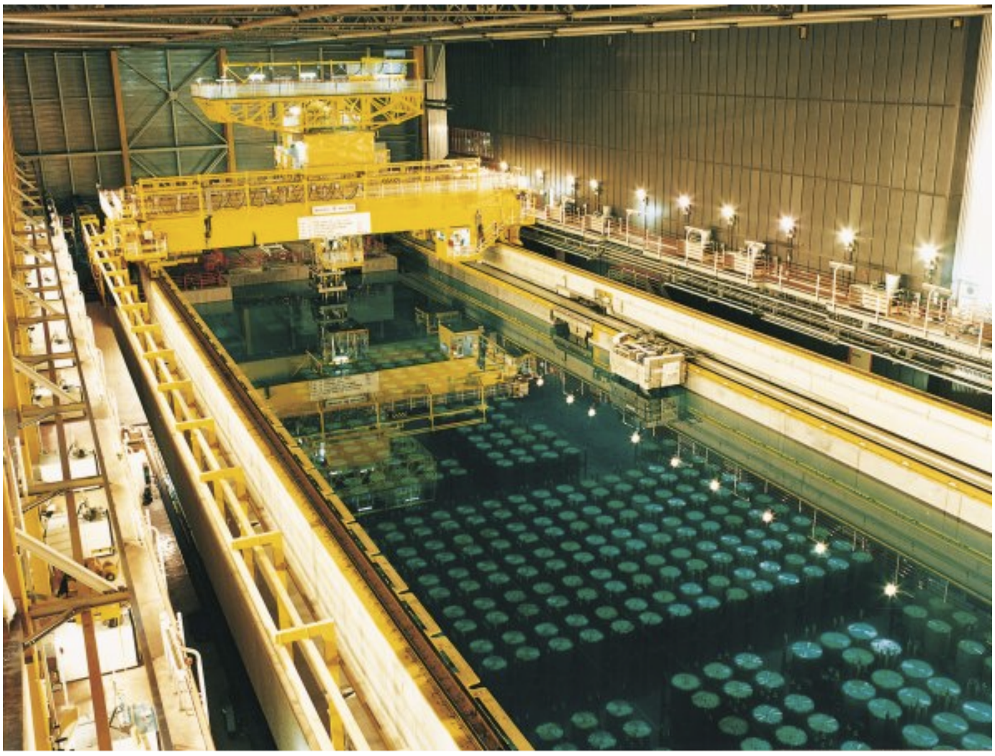

Figure 3. Water-cooling tank for 5-year storage of spent fuel rods. The water is a radioactive shield. The circular patterns beneath the water are caskets of waste fuel rods. (www.world-nuclear.org)

It is possible to recycle the nuclear waste through processing and use it again in a nuclear reactor. France, Japan, England, Sweden, and Russia do this now. Reprocessing salvages unused plutonium and uranium reducing the volume of waste and keeping the option open to use these elements later as nuclear fuel. The US does not recycle. It is again a political challenge with anti-nuclear proponents fighting hard against recycling waste because it means that we will commit to keeping the nuclear reactors going. Not a good argument, but logic often has a tough battle in the nuclear power arena.

Sandia National Laboratories designed highly secure casks for storing and transporting nuclear material. Their severe tests included crashing a jet aircraft into a cask, crashing a rocket assist diesel locomotive into a cask (Fig. 4), and immersing the casks in intense oil fires. All casks survived. The capability exists to produce a cask that will withstand severe environments.

Figure 4. A yellow diesel locomotive about to crash into an orange cask at more than 80 MPH. The train virtually exploded the trailer platform, and the cask survived. (Sandia National Lab). http://www.youtube.com/watch?v=1hjwa91As1A

Hore-Lacy reported in 2008 that since 1971, 7000 world shipments of used fuel traveled over more than 19 million miles, with no breach of security [12]. The US had made 300 land shipments of nuclear fuel over 1.7 million miles without an accident. By 2008, over 300 ocean cargo vessels had carried radioactive waste without radiation release. However, in 2010 the Canadian ship Altona ran into a heavy Pacific storm enroute to China. It was carrying the uranium ore concentrate yellowcake, and the storm broke casks spilling the yellowcake. These were presumably not the US Sandia Labs casks. The main concern was inhalation of the uranium oxide UO_8. The ship returned to Canada for cleaning without health problems, and lawsuits were filed as the ship sat in Vancouver Harbor.

Nuclear waste has not been a security risk, but permanent secure storage has. If the US decides to recycle nuclear waste, then more fuel is available, and the waste volume is reduced. In the later chapters we will study two types of nuclear reactors that can use waste as a fuel: the Thorium Reactor and the uranium Integral Fast Reactor (IFR).

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Chapter 16

Nuclear Power V

Unfortunately, nuclear reactors are typically not evaluated on their properties, but on public perception, especially fear.

We have come a long way in three chapters, and now let's clean up some important LWR loose ends. How much uranium is left, the economist Mark Cooper's challenge to industry that nuclear reactors fail well before expected life is a list of LWR deficiencies, decommissioning a nuke, are the rules fair in competition with coal and gas, the human death rate myth attributed to nuclear reactors, high tech military style security, and terrorism.

How Much Uranium Reserve Do We Have?

Steve Fetter reported in Scientific American in March 2009 that the world has about 200 years of natural uranium at the current rate of consumption. It takes about 10 metric tons of uranium to make one ton of 3% enriched uranium leading to 70,000 metric tons of natural uranium mined per year. And these reactors use 1% of the fuel and create 99% waste. These numbers vary with the particular design of a nuclear generator and the mining source. The World Nuclear Association estimates that with current technology, the US has low cost uranium reserves for about 80 years. So, between 80 – 200 years is a rough estimate using current technology. So, do the words "I will be dead by then" ring in our ears.

When better ways exist, why not move on. Breeder reactors would extend the uranium life to 30,000 years. Seawater extraction of uranium predicts a 60,000-year supply at present consumption rates. Part II coming up will address better ways.

The lifetime can be significantly increased with other approaches. Liquid (molten) salt breeder reactors in the next chapter use of 99% of the fuel to generate electricity with 1% waste. Molten salt reactors operate at atmospheric pressure so that they don't have the steam or hydrogen explosion problem

Economic Analysis Threatens LWR Nuclear Power

There is a serious concern with nuclear power that is unrelated to fear. Mark Cooper, an economist from the University of Vermont Law School, raised a troubling equipment reliability issue and that is the finite life of an LWR nuclear plant [1]. LWR nuclear plants are licensed to last 40-60 years with little down time. But recent data show serious problems after 30 years. Nuclear reactors are expensive and time consuming to build and repair. LWR nuclear power plants grow old too soon, and there is no assisted living facility for a reactor. The difficult choice is whether to repair or shut down.

The average age of the 65 current US nuclear plants is about 32 years. These 65 plants contain about 100 nuclear reactors producing about 19.5% of US power. Nine major nuclear reactor early closures occurred in 2013, and 38 reactors in 23 states now face early retirement. 12 are at risk of shutdown, according to Cooper. The high average age of the US nuclear reactors is attributed to a 30-year moratorium on building new nuclear reactors. The Nuclear Economics Consulting Group (NECG) lists ten nuclear reactors in the world that are over 44 years old with seven being in the US (http://nuclear-economics.com).

Mark Cooper and the three investment firms of Credit Suisse, Moody's, and UBS reported disturbing reliability trends [1]. The total LWR nuclear plant outage days increased from 3,157 days in 2008 to 5,126 days in 2012 without a significant increase in the total number of plants. This is an outage increase from 8.3% to 13.5%. Ten nuclear plants were off-line more than 100 days compared with a four-year average off-line of four nuclear plants in the preceding four years.

Four nuclear plants permanently shut down in 2012-2013. One was retired for economic reasons (Kewaunee, WI), and three for excessive repair cost; two in San Onofre, CA and one in Crystal River, Florida, (Fig. 1 a,b). The Vermont Yankee nuclear plant was licensed in 1972 and relicensed in 2011 to the year 2032. However, the plant closed in 2014 because "the Vermont Yankee is no longer financially viable." An additional twelve reactors have symptoms making them "reactors at risk."

(a)

(b)

Figure 1 (a) Two San Onofra LWR nuclear reactors shut down at age 29 years (www.kpbs.org); the cause was tubing wear issues, (b) The Crystal River LWR nuclear reactor shut down at age 32 years, the cause was cracks in containment structure. Both nuclear reactor sites closed for too expensive to repair.

(http://www.remotevisualinspection.org)

The Tampa Bay Times wrote in February 2014 that the St. Lucie nuclear plant of Florida Power and Light Corp. found wear spots in tubing in two steam generators that were similar to those found at the San Onofra plant in California. The steam generators showed 1,920 wear spots that were 20% deep. Wear spots grow in frequency and depth. It is a design challenge for these very thin walls of these heat exchanging tubes.

Age and reliability failures are expected for any products, but nuclear failures can be billion-dollar repairs. The average cost of an LWR repair is \$1.5 billion with one repair cost at \$11 billion. Even more painful is that nuclear fuel and the costs of operation and maintenance are exceeding inflation. So, if you are a CEO of a utility company with a reactor over 30 years old (or younger), do you invest your money in repair, or scrap the operation in favor of cheaper gas? The industry is money driven.

In many areas of the country, the lower price of natural gas sets the "clearing price" that other energy sources must match. Nuclear plants must compete with that price, and it has put nuclear on the edge of profitability.

Cooper's economic data throw a challenging spear into the heart of the current LWR nuclear industry. A question is whether 3rd or 4th generation nuclear reactors can demonstrate a reliable 40-60 years of operation. The current aging LWR reactors were designed in the 1980s. There are 4th generation designs now available with better safety features and hopefully better reliability. Can nuclear reactors be "designed for repairability" as occurs for other products? Can reliability be demonstrated? Is this reliability root-cause problem insurmountable? Can mass production of a single design bring down costs? Can we afford to not spend this money?

A traditional general engineering response is to identify reliability failure mechanisms and eliminate them. Reliability is extensively analyzed in the electronic industry, but chips are smaller, cheaper, and easier to accelerate failure mechanisms and pinpoint failures. But running from a reliability problem is not what engineering practice is about.

Robert Trigaux was the Business Editor of the Tampa Bay Times, and he pointed out another problem that the nuclear industry has created. Florida (and other states) has allowed state legislators to pass laws assessing customers for power plants yet to be built. This was a particular sore point when years later the proposed Levy County nuclear reactors in Florida were cancelled with no payback to ratepayers. Next, the money needed to decommission the neighboring Crystal River reactor was again passed on to the customers. State legislatures gave shareholders a free ride at customer's expense. Trigaux also pointed out that bankers are reluctant to sink money into a business with an increasingly bad track record. The federal government is the third source of money offended by these results. Public relations are critical in nuclear and some of the renewable energy sources. A power company can become its own worst enemy.

Peter A. Bradford is a former member of the U.S. Nuclear Regulatory Commission (NRC), and a former utility commission chair in New York and Maine. He said: "*No U.S. nuclear plant has ever closed because it reached the end of its licensed life. Instead, a cost challenge to their continued profitability has usually been the cause of shutdowns.*"

Throwing Rocks at the LWR

The LWR is the most popular nuclear reactor used today with about 70% of the world market. It has many advantages, and many support it as necessary to combat the serious deficiencies of coal and gas. But opponents often attack nuclear power for the wrong reasons, focusing on fear and waste. We summarize the other LWR technical weaknesses.

- The LWR burns only 1% of its fuel load and produces 99% radioactive waste

- The LWR cannot burn its waste or that of other LWR plants
- Reliability failures and early decommissioning after 30 years of operation is a serious problem
- Repairs are often too costly to fix
- LWR requires an expensive high-tech security force
- Natural uranium requires 3% - 5% enrichment of ^{235}U
- If the fuel core is not covered with water, the core melts
- LWR has no passive safety shutdown (Westinghouse AP1000 is exception)
- LWR uses high pressure-temperature steam, which is the major reason for explosions and the need for a strong explosion containment structure
- Turn-on and turn-off times are 1-2 weeks
- The cost of a new LWR nuclear plant is now many billions of dollars

LWR Nuclear Plant Lifetimes and Decommissioning

Forty years seems like a long time when the startup license is signed, but it is not. Decommissioning a nuclear plant means that its useful life is over, and the physical facility must be shut down with all traces of previous radioactivity removed. The cost to decommission a plant ranges from about $300 million to $500 million. One aging problem is the constant bombardment of materials by high-energy neutrons. Another reliability problem is mechanical fatigue. In contrast, dirty coal plants are operating that were constructed in the 1960s. The equipment of a coal plant can be more easily replaced to keep coal plants in operation for a long time.

Reactors that suffer a meltdown must be decommissioned. The damaged Three-Mile Island cost about $837M to decommission, and Fukushima Daiichi cleanup is estimated to cost about $100 billion.

Are Nuclear Reactors Treated Unfairly?

“Unfairly” may be a bit off the mark, since all is fair in love, war, and the electric power industry. But coal does seem to get a free ride with respect to its abundant sins. The 28 radiation deaths in Chernobyl in 1986 remain fresh in the minds of anti-nuclear groups, while coal silently kills tens of thousands of deaths per year in the US and over a million in China. Coal miners suffer mining accidents and black lung disease, but these facts get little news and are soon forgotten. Coal strip mining in West Virginia rips the top from the beautiful Appalachian Mountains. Nukes do not. The regulated radioactive smokestack emissions of coal are three times higher than for a uranium nuclear condensation exhaust, but there are no data to justify this requirement in either technology.

The coal waste, or slag, is about 10% of the weight of the coal burned, and it should be an issue. An accidental slag dump covering 70 miles of the Dan River by Duke Energy in North Carolina in 2014 briefly made national news but is now forgotten by the public. The worst sludge accident occurred in 2008 at the Kingston plant in eastern Tennessee where a sludge pond collapsed (New York Times, April 16, 2017). About a billion gallons of sludge waste emptied into the Emory River that joins the Tennessee River. The sludge covered 300 acres of land with toxic material containing arsenic, mercury, lead, and heavy metals. The point is that the slightest nuclear waste spill such as the Fukushima- Daiichi release into the Pacific Ocean caused alarming news reports that linger.

So, what is the deal? Nuclear has expensive regulations that prolong construction. Some regulations are correct, and others are a mystery. The multi billion dollars per year high tech security imposed on nuclear should be evaluated with respect to the threat. No other power generating technique has such a security mandate. A coal or gas plant may have only a barbwire fence even though a terrorist attack on a major power plant can significantly affect our power capability and strike fear. Nuclear reactors do not emit smoke but do emit water condensation in their cooling towers. There are no data to support that nuclear water vapor emissions present a hazard. Scientific American Magazine reported in December 2007 that

> *"Over the past few decades, however, a series of studies has called these stereotypes into question. Among the surprising conclusions: the waste produced by coal plants is actually more radioactive than that generated by their nuclear counterparts. In fact, the fly ash emitted by a power plant—a by-product from burning coal for electricity—carries*

> *into the surrounding environment 100 times more radiation than a nuclear power plant producing the same amount of energy*."

But meeting a lower radiation standard puts a significant cost burden on nuclear. While the water reactors (LWR, BWR) have problems to solve, the deal is that nuclear generators are crippled by questionable regulations not imposed on coal or gas generators.

Uranium Mine Operation and Safety

Serious uranium mining really began with weapon development in the 1940s. Today Australia, Kazakhstan, and Canada are the major uranium suppliers. Early mining in the United States took place in the west, particularly in New Mexico, Colorado, and Arizona. Figure *2* shows an open pit mine in Spor Mountain, Utah.

Figure 2. A uranium surface mine in Spor Mountain, Utah. http://world-nuclear.org

Miners inhaled silica dust and radon gas in the early uranium underground mines. ^{235}U is a toxic metal as well as a radiation hazard, and latent lung cancer appeared in these early miners. Today, open surface mines, radiation monitoring, and ventilation of underground mines have reduced these hazards to levels of the general population. Since these improvements, there are no instances of increased health problems with the uranium miners. Fatalities are now rare in uranium mines. A miner died in Utah in 2010, and he was the first mine death since 1998 [3].

Uranium ore is taken from underground mines, surface mines, or *in-situ* mines that dissolve and extract the desired uranium but leaves the underground material in place. Raw mined material is crushed into particles, and then drenched with an acid to put the uranium into a solution. The undissolved material becomes the mine tailings. The tailings retain a significant uranium radioactivity including radon gas and groundwater risk as happened around the Jack Pile Mine in New Mexico in the 1970s.

Radon gas is a transmutation from uranium to radium to radon, and it is found in unhealthy concentrations in underground mines. Radon can cause lung cancer, and it is found in buildings and homes that concentrate the gas from the ground underneath the structure. Ventilation is the prescribed solution in homes with radon especially in the crawl spaces beneath the house. The EPA lists 21,000 US non-mine related deaths per year in 2010 in the general population due to elevated natural radon-induced lung cancers.

Another Nuclear Fatality Myth

Public fear imagines that nuclear reactors are or will be responsible for millions of radiation related deaths. The death rate, or death print, for various energy source technologies is given in Fig. 3. The numbers are global unless labeled otherwise. Coal is by far the worst, and nuclear has the impressive lowest death print. The data are approximate since variables such as the number of power plants in each energy source, and safety in manufacturing and installation differs for each source. But clearly, low dose nuclear environments are more than three orders of magnitude safer than coal and about 100 times safer than natural gas.

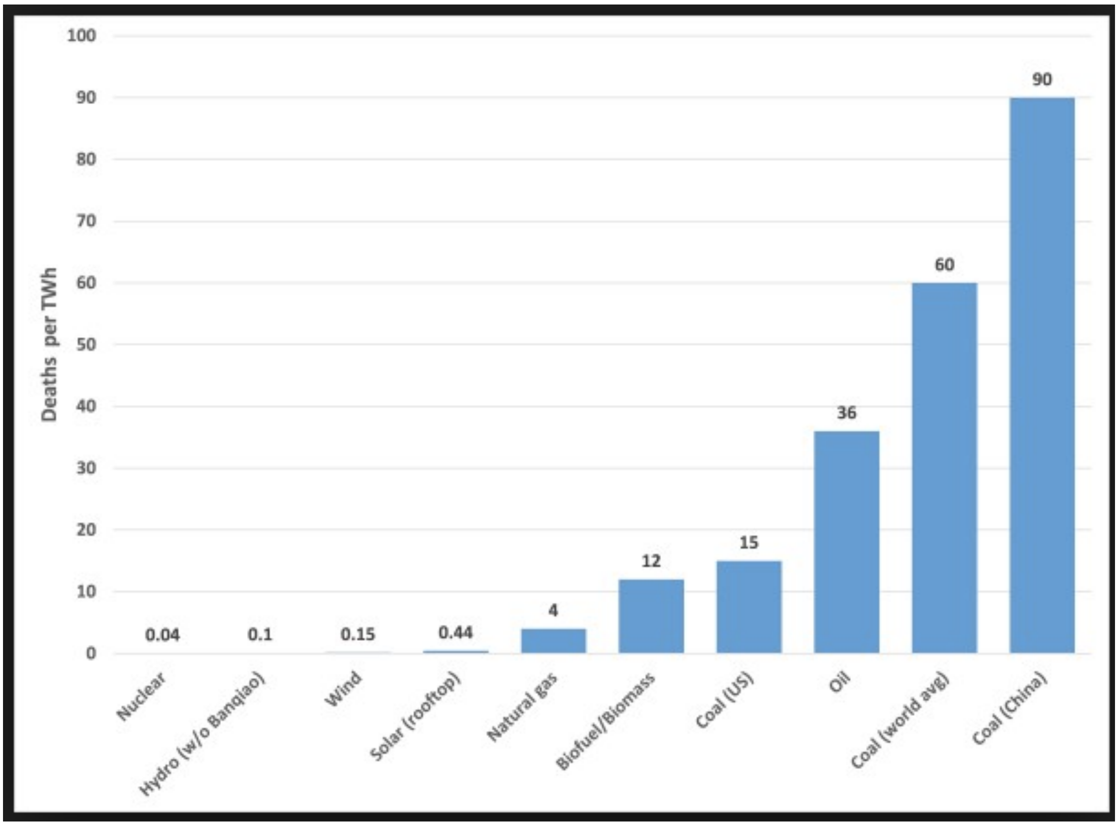

Figure 3. Energy source death rate comparison. (Nuclear Economics Consulting Group (NECG) and http://nextbigfuture.com)

Two major factors drive our decisions in baseload energy choice. One is corporate drive for the lowest cost. Second is public acceptance, or rejection, of a particular technique. Coal and gas are mostly the corporate choice with a long history with coal. Nuclear energy growth is mostly plugged up with public fear of nuclear and utility fear of cost, despite no evidence of the perceived danger of low-level radiation. Public health, climate change reduction, environmental damage, and miner safety should lie at the top of the list for decision making. They are not, and that is where the US stands.

Nuclear Plant 24/7 Security

All electrical generator plants have security even if only a barbed wire fence. But nuclear plants are unique in that the US government imposes strict security regulations. It is a high-tech military type of security contracted to private companies that protect nuclear plants (Fig. 4). The Nuclear Energy Institute reports that there are about 9,000 highly trained and armed security guards to protect 65 nuclear plants and 104 nuclear reactors. That is an average of 87 guards per reactor or 138 guards per site.

Figure 4. Nuclear security force at the now decommissioned Crystal River nuclear plant in Florida. (helloartichokeannie.blogspot.com

Typical nuclear security salaries range from about $19,000 to $29,000 for mid-level workers and about $60,000 for nuclear engineers. If we assume that overhead is 100% and total employee costs average $100,000, then total salary costs are about $900M per year. The average is about $1.15M per month for each of 65 sites just for security personnel.

Nuclear security has additional overhead costs that require expensive intrusion detection equipment in a system that runs 24/7. Training, office space, maintenance and office heating, personnel clearance costs, weapons, ammunition, vehicles, threat exercises, and company profits are continuous. Cyberattack is a significant part of the security mission. These multi-billion-dollar costs do nothing for making the energy generation process more efficient.

Nuclear Terrorism

The 9/11 attacks on the World Trade Center sobered the US, and attention increased on the nuclear power industry reactors. The images of Fukushima Daiichi and Chernobyl played out in many minds that something a saboteur could reproduce. While damage is possible, setting off an atomic bomb at a power plant is not. The 3% - 5% enrichment for the nuclear reactor is not close to the 90% required for an atomic bomb. Also, an A-bomb requires a sophisticated triggering mechanism.

What can intruders accomplish? The NPPP report from the University of Texas listed [4]:

- Stealing a nuclear weapon, (Not likely from a power plant)
- Theft of fissile material such as plutonium to build an improvised nuclear weapon
- Sabotage of reactor by aircraft attack, vehicle bomb, anti-tank weapon, or disabling of cooling pumps by an insider
- Theft of spent fuel rods in the fuel decontamination pool

Some thoughts: Sabotage is easier than theft. Stealing fuel rods from a reactor site would be a major challenge, and radiation would probably kill persons who handled unshielded fuel rods. The stolen uranium fissile material would have to be enriched from 3.5% to 90% - a possible but difficult task.

Airplane crashes were studied. A Boeing-767 airliner with a full load of fuel was simulated. The airplane is much wider than the reactor containment diameter so that much of the aircraft mass misses the target structure. The plane must reduce its speed to around 350 MPH to maintain flight stability at this low altitude, so momentum is decreased. The study concluded that a large jet aircraft would not penetrate the reactor containment structure. Aerial cables suspended near the reactor might be a cheap way to reduce risk.

Summary

Unfortunately, nuclear reactors are typically not evaluated on their properties but on public perception. If there were evidence of nuclear fatalities, radiation poisoning, greenhouse gas emissions, poor public safety, biological mutation, terrorist attacks, then we would agree with these fears. *But, on the contrary, there have been* <u>*none*</u> *of these factors in the US due to nuclear reactors in over 65 years of total commercial and military power reactor development and operation.* Nuclear greenhouse gas emissions are near zero. There are no records of mammalian mutations or terrorist attacks. Extensive studies of low-level radiation show no elevation of cancer rates above normal data. In fact, many regions show a decrease in cancer rates. The LNT model should be scrapped, and regulations based on scientific measurements introduced to define safe and unsafe radiation levels. This would significantly reduce nuclear startup costs. This is what the data show.

While nuclear has clear advantages over coal and gas, LWR nuclear reactors must solve their problems. A glaring weakness of current LWR nuclear power is that only 1% of the fuel is used and 99% is radioactive waste. New alternative nuclear designs target 99% fuel burn up. Three other problems for nuclear engineers are: the long-term reliability failure mode identification, fixing those reliability problems of aging reactors, and addressing the nuclear waste issue.

We should not build reactors near tectonic fault lines, or near an ocean (San Onofre, California is being shut down, but it had both). Japan has all of its 44 nuclear reactors on the Pacific Ocean coast. Japan needs dependable water for its reactors. Nuclear construction costs are high, but not when averaged over the life of the reactor. When health, fatalities, and greenhouse gas emission costs are weighed against coal and gas, then LWR and BWR nuclear are better choices.

The next three chapters will describe the Thorium Nuclear Reactor, the Integral Fast Reactor (IFR), and the Fusion Reactor that eliminate waste by burning near 100% of their fuel. These designs remove the serious objections to the LWRs, coal, and natural gas.

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March 22, 2022

PART II

ADVANCED NUCLEAR DESIGNS

Cleaner, Cheaper, Simpler, Safer, and Longer Fuel Resources

Chapter 17

Thorium Reactor I

We propose the burning of this thorium dissolved as a fluoride in molten salt in the minimum viscosity mixture of LiF and BeF2 together with a small amount of 235U or plutonium fluoride to initiate the process to be located at least 10 m underground. ... the power plant could operate for up to 200 yr with no transport of fissile material to the reactor or of wastes from the reactor during this period ... the fuel leaves the reactor core, always near or at atmospheric pressure ... This heat is converted to electricity in a modern steam power plant at an efficiency of ~ 43% ... We call for the construction of a small prototype thorium-burning reactor. [1]

Ralph Moir and Edward Teller, 2005

Why was there more than a 30-year pause between proof of thorium concept and later recognizing the importance that a thorium reactor might have for our future power generation? Thorium was not a stranger. Marie and Pierre Curie investigated thorium and other radioactive elements over a hundred years ago. Thorium was researched during the Manhattan atomic bomb project, but it was found much less efficient than uranium for making a nuclear explosion.

Alvin Weinberg, the Director of ORNL was heavily involved in uranium research in the 1940s. He patented the uranium LWR high pressure steam turbine design that we use today, and he advised Admiral Hymen Rickover to use the LWR design for the Nautilus submarine [2]. Ten years later Weinberg led his

ORNL group on an investigation of the many ways a small lightweight nuclear reactor could be built. He settled on the wonders of the thorium reactor design, and ORNL then built one that worked as anticipated. He was excited about the thorium reactor taking over commercial power, ship propulsion, and water desalination.

The obstacle was Rickover whose power had risen as head of the Atomic Energy Commission on successes of the *Nautilus* and the commercial nuclear plant at Shippingport, Pennsylvania. Rickover removed Weinberg as Director of ORNL for not supporting the AEC's direction of nuclear research. In 1973 the thorium work was cancelled. Rickover's decision was personal as well as military.

About 30 years later a young NASA spacecraft engineer named Kirk Sorensen happened on a paper describing the thorium molten salt reactor work of Weinberg's ORNL team [3]. Kirk became the resurgent thorium reactor driving force, and he digitized and made available many ORNL research papers free on the Internet. A small group of physicists and nuclear engineers in favor of this method began to grow.

The Thorium Energy Alliance and its Annual Conference (TEAC) began and whose presentations are available on YouTube.com. Other nations had or began research programs. China, India, England, France, Brazil, Japan, Norway, Canada, Czechoslovakia, and Russia have thorium programs typically with government support. The Chinese government appears the thorium technology leader at this point employing 700 technical workers, and the interesting connection that ORNL was an early consulting partner [4]. China says publicly that all intellectual rights uncovered will belong to China. In 2020, China announced that it had built a 2 MW thorium reactor and that it operated as expected. .

The USA has a patchwork of small private companies trying to get financial support and inch forward to the thorium goals. Kirk Sorensen's Company FliBe Energy (pronounced Fleeb) is aiming for a prototype in the 2020-time frame working around the immense challenge and time delay of writing regulations for a new nuclear technology.

What is the holdup?

According to John Kutsch, the biggest obstacle outside of China is financial commitment from a government budget [4]. China spends almost $2 billion dollars and has a team of 700 employees. The American commitment includes about a dozen startups with about $1 - $2 million dollars each, and that is not sufficient to achieve hardware goals of a thorium molten salt reactor in a reasonable time. .

Other challenges are to achieve a reliability that will last 40-60 years. There is the material science problem of salt induced corrosion in the face of higher temperatures and constant high radiation. A bigger challenge is the political and public resistance to a technology that disrupts the present coal, gas, BWR, and LWR reaction uranium industries. And fear over the words “nuclear reactor” exists in too many people. And approval licenses can take a few years for conventional LWR reactors. There is currently no license for thorium reactors. But strong government support is needed.

A cost estimate for a thorium Small Modular Reactor (SMR) powered to 200 MW is $200 million [5,6]. The SMR would be mass produced, and partially assembled at the factory. The full SMR would be installed at the site in bigger pieces of preassembled portions. Construction of a nuclear reactor becomes installation.

Richard Hargraves uses an analogy to the Boeing 787 airliner manufacturing approach that delivers one every 3.5 days. The cost saving and delivery of prebuilt one a day SMRs, that would be truck delivered to a site are quite possible [1,3,5]. The comparison of the two years and nine months’ time to demonstration of a nuclear chain reaction and atomic explosion should not be lost when urgency drives a nuclear project. Now let’s look at how a thorium reactor works.

How Does a Thorium (Th) Reactor Work?

This section gets a bit tedious, and you may want to skim read. The Th-reactor has been described as a chemist‘s reactor. Don’t let that scare you, as we get a sense of the basic principles [5,7,8]. Figure 1 shows a Th metal sphere. Thorium has a half-life of about 4.3 billion years, which means that it takes a very long time to completely lose its radioactivity. It is barely radioactive at any time. Thorium can be held in your hand. It has been used for jewelry for many years. When Th is mined, it requires chemical separation and cleaning, but no enrichment.

Figure 1. A thorium ball is not radioactive in its stable isotope. You can hold ^{232}Th in your hand. (www.youtube.com)

It is not a stretch to say that the thorium reactor and the uranium Light Water Reactor have virtually nothing in common except generating electricity. They both build their operation on the same nuclear physics, but the manipulation of that physics and engineering is totally different.

Thorium (Th) in the Periodic Table in Fig. 2 has an atomic number of 90 (protons) slightly below uranium of 92. Thorium's atomic weight (sum of protons and neutrons) is 232 in its stable isotope (^{232}Th), and it is abundant in the earth's crust. It has been considered as a nuclear fuel source with uranium since the 1940s, but research ended in the late 1980s from political decisions. Today, Th has a resurgence and brings outstanding properties for electrical power generation.

Thorium is not fissile meaning it does not spontaneously fission. It has to be coaxed. If a slow-moving neutron is absorbed by a thorium nucleus, then ^{232}Th undergoes a sequence leading to the fissile ^{233}U (Fig. 3). ^{232}Th breeds fissile

^{233}U. A β^{-} particle emission increases the proton count by one by converting a neutron in the nucleus to a proton increasing the atomic number but leaving the atomic weight unchanged. The sequence is

$$^{232}\mathrm{Th}_{90} + \text{slow neutron} \rightarrow {}^{233}\mathrm{Th}_{90} \xrightarrow{\beta^{-}} {}^{233}\mathrm{Pa}_{91} \xrightarrow{\beta^{-}} {}^{233}\mathrm{U}_{92} + \text{Fission}$$

Fission release = neutrons + β-particles + heat + fission daughter atoms

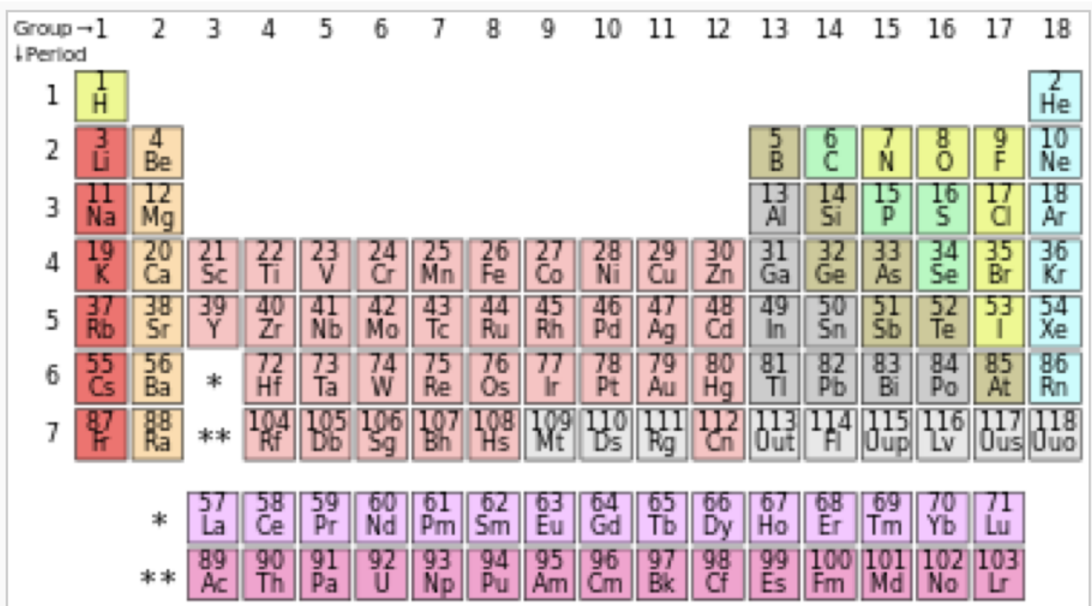

Figure 2. Periodic Table showing the heavy metals Th, U, and Pu in the bottom row.

There are two major processes in a Th-reactor core (Fig. 3). The fertile ^{232}Th is in a *blanket* space around the ^{233}U core. A graphite partition moderates (slows) the fast neutrons emitted from the core that go into the blanket. Thorium is dissolved in a molten fluoride salt that supports the Th fuel and is also the primary coolant salt of lithium and beryllium.

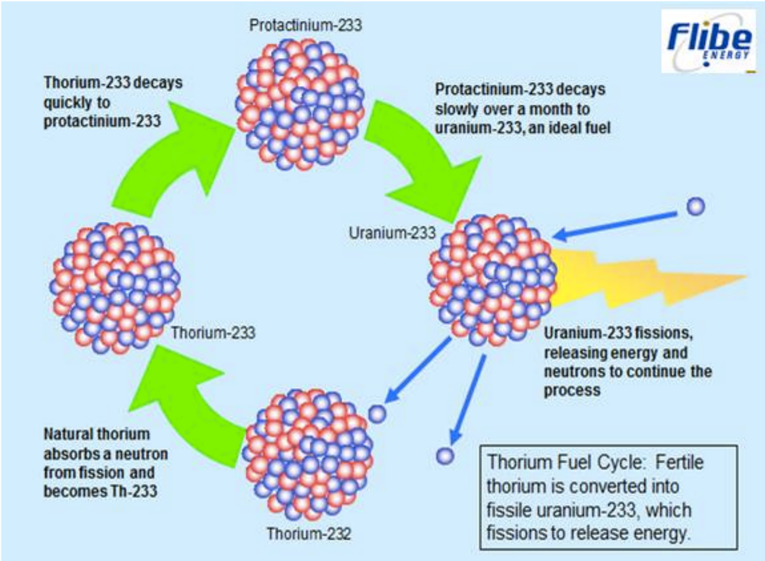

Figure 3. The thorium fuel cycle. All atoms are contained in the reactor molten salt and form a closed loop. Preexisting ^{233}U in the core fissions and emits fast neutrons slowed by a graphite moderator some of which are absorbed by the nucleus of blanket ^{232}Th atoms briefly forming ^{233}Th. ^{233}Th decays to ^{233}Pa that decays to fissile ^{233}U completing the feedback loop. Thorium is not the fuel that generates heat to drive turbines, but it breeds fissile ^{233}U whose fission in the core releases energy, daughter atoms, and neutrons. The molten salt pipes that allow transfer of ^{233}U from the blanket to the core are not shown. Neither are the plumbing and portholes that allow separation of waste elements from each section. (Figure from Flibe Energy Inc.).

The thorium salt mixture is: $LiF\text{-}BeF_2\text{-}ThF_4$ (Fig. 4). The lithium and beryllium salts are chemically stable. Fluoride salts have low vapor pressure, carry more heat than the same volume of water, have good heat transfer properties, have low neutron absorption, are not damaged by radiation, do not react violently with air or water as liquid sodium does, and are inert to some common structural metals (World Nuclear Assoc.).

Figure 4. Molten salt and fuel: $LiF - BeF_2 - {}^{233}UF_4$

www.militaryphotos.net

The other functional unit is the *core* that takes ^{233}U from the blanket and generates the reactor fission heat. It continues the reaction cycle by injecting fast neutrons through the thick graphite-moderating material (Fig. 5). Figure 5 is a block diagram and doesn't look like the real pipes and containers. The molten salt supports the recently generated ^{233}U and the ^{232}Th inside the blanket. The ^{233}U is removed from the blanket and injected into the core where it fissions creating the heat to drive the reactor. It sounds complicated and it is, but at atmospheric pressure the molten salt is accessible through portholes in the pipes where ^{232}Th can be replenished in the blanket.

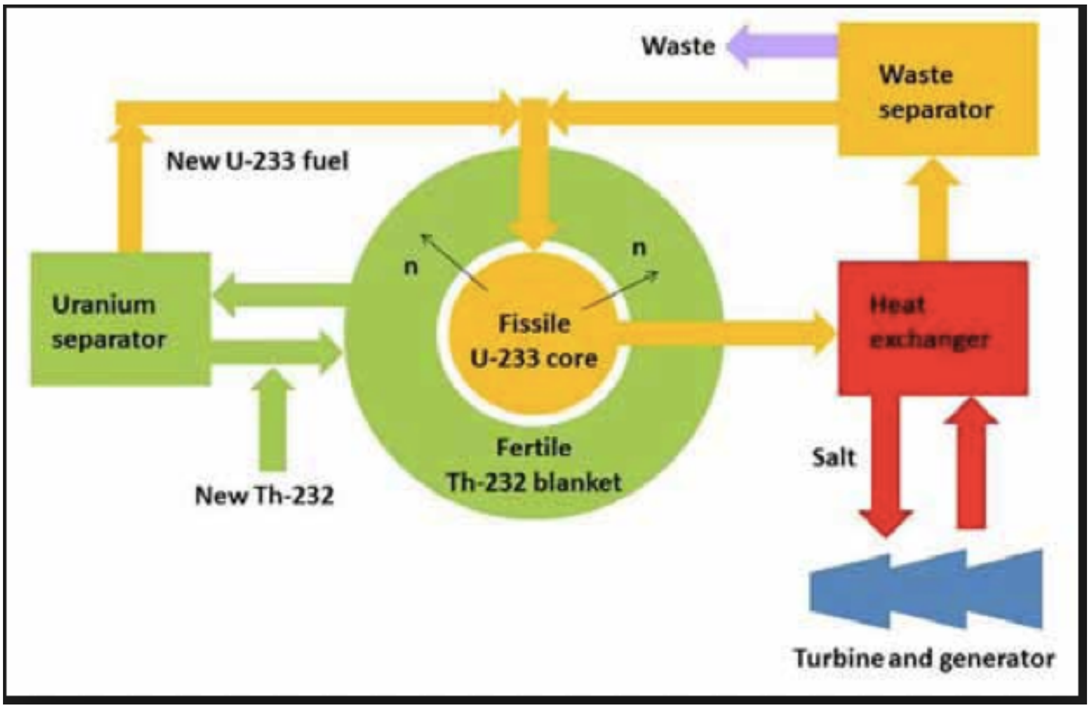

Figure 5. Schematic of LFTR. A starter fuel (^{233}U) in the core (yellow) emits fast neutrons that are slowed by the graphite (white). The slow neutrons entering the blanket are absorbed by ^{233}U initiating a complex chain reaction that transmutes ^{233}Th to ^{232}Th to ^{233}U. ^{233}U is the fuel that fissions creating the heat to drive the generator. (www.aps.org)

^{232}Th needs slow neutrons (thermal neutrons) to initiate the transmutation to ^{233}U. Graphite moderates (slows) the fast neutrons ejected from the ^{233}U core. The graphite may be a meter thick, and it is shown as the white separator circle in Fig. 5. The molten liquid LFTR is much different than a solid fuel LWR. There is no water in the LFTR, and the high reactor temperature can be air-cooled. This removes the requirement that the Th reactor be located near a water source.

The molten salt melts at 434 ^{o}C and boils at 1430 ^{o}C. This means that between 434^{o}C and 1430^{o}C, the molten salt will neither be a solid nor boil away. At a core temperature of 900 ^{o}C, the fuel is molten, and significantly the LFTR molten salt is kept at an ambient atmosphere pressure. A fissile starter element in the core is needed to generate the initial slow neutrons to start the reaction in the blanket.

The starter element can be ^{233}U, ^{235}U, or ^{239}Pu. The heat exchanger transfers heat from the core primary loop to a secondary loop that drives a gas turbine generator. The two loops are physically isolated in the heat exchanger.

The reactor can be refueled, and chemical byproducts removed without shutting down with fresh molten thorium salt entered through a port. The fuel circulates continuously in the core and primary coolant loop. Waste products from ^{233}U can be removed in the primary coolant loop through a port. These are not easy steps, but it works. The reaction will continue as long there is ^{232}Th in the blanket. Remove the ^{232}Th and the reaction stops. A LFTR reactor can be designed to burn three fuels: (^{233}U), (^{235}U), or (^{239}Pu) bred from ^{238}U.

The molten salt has three other advantages. The fluoride salts will bind the ^{233}U waste product xenon-135 that poisons the reaction in an LWR. Xenon-135 is easily removed in a LFTR. The salt solution can be directed by gravity in emergency situations to a container below the core, and meltdown is not possible since the fuel salt is already in a melt state.

LFTRs use a gas turbine in a heat engine model called a Brayton Cycle. First think of a jet engine with hot gas entering the turbine blades, expanding as it burns and driving through the blades. In this design, the air intake of oxygen is burned with fuel to produce water, CO_2, NO_2, and no oxygen as it blasts out the exhaust. A better design generates the hot gas in the LFTR core, and that hot gas is run through a heat exchanger transferring heat to the input air. The exhaust air then contains the same 20% oxygen and 80% nitrogen that entered the heat exchanger. The air exits the exchanger eliminating the burn. There is no CO_2 emission. The Brayton Cycle has the Carnot engine temperature efficiency dependence with up to 55% reported.

The LFTR is auto controlled for the generated load power change. As power and temperature increase, the liquid expands, and interatomic distances increase. The nuclear criticality decreases with larger atomic distances, and power generation is reduced. Overheating is self-controlled, and this process is called a load follower design. As the core cools and the atomic distance contracts, the efficiency and power generated increase. The reactor power generated is auto controlled by the load demand. A run-away thermal reaction does not happen.

The electric utility industry is technically sluggish. This is not an insult, but a fact traced to its historic adherence to its generation, transmission, and distribution design. The industry is heavily invested in Nikola Tesla and Thomas Edison's design of the 1880s. One modern challenge is how to handle millions of renewables injecting power (current) into the utilities grid without destabilizing the power grid [8,9]. The thorium reactors remove the need for modern renewables.

References Chapter 16 Thorium I

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Chapter 18

Thorium Reactor II

The total energy of the universe does not change
(1^{st} Law of Thermodynamics)
Albert Einstein

Oak Ridge National Laboratory (ORNL) and the Idaho National Lab (INL) demonstrated two prototype molten salt reactors in 1954 and 1969 that used ^{233}U as a fuel (Fig. 1) [1]. The first commercial nuclear reactor in Shippingport, Pennsylvania operated for five years and used thorium to make the ^{233}U. Safety tests run at INL verified that the reactor safely responded under various emergency conditions. These two reactors completed the prototype demonstrations of a LFTR. We will restate and extend the thorium reactor properties.

Figure 1. The Oak Ridge National Laboratory (ORNL). The molten salt reactor (MSRE) demonstrated fueling with ^{233}U and ^{235}U from 1969-1972. From 1977-1982, the nuclear reactor at Shippingport, Pennsylvania used liquid ThF_4 thorium to generate ^{233}U to complete the LFTR demonstration. The thorium plant delivered 60 MW.

The Aircraft Engine Nuclear Reactor project at ORNL began in 1954 and the Molten-Salt Reactor (MSR) Experiment from 1965 to 1969 used liquid fluoride fuel salts. In 1969, the ORNL MSR operated continuously for 2.5 years circulating molten fluoride salt at 650 ^{o}C with ^{233}U as the fuel with a power output of 7.4 MW. In 1977, the nuclear reactor at Shippingport, Pennsylvania used pellets of thorium ThO_2 to demonstrate the fuel link from ^{232}Th to ^{233}U in a single commercial reactor (Fig. 2).

Figure 2. The Shippingport, Pennsylvania reactor was the first full-scale commercial LWR nuclear power plant in the United States. Later it demonstrated the thorium ^{232}Th to ^{233}U conversion and subsequent power generation from 1977-1982.

The LFTR operated successfully at Shippingport for five years delivering 60 MW before the facility was shut down. These are the hard prototype data that demonstrated the LFTR proof of concept. Then political catastrophe struck, and the LFTR work was canceled. ORNL was ordered to terminate the molten salt reactor (MSR) program in deference to the uranium LWR.

The LFTR defines the near perfect reactor. But thorium faces major challenges to move to a commercial product. Thorium is a disruptive technology, and therein lays a big problem. The present uranium LWR and BWR reactors are part of a successful, lucrative 65-year business and engineering practice. The nuclear private industry has invested heavily in LWR technology, and it does not have the resources or desire to conduct research and development in thorium. That should be the role of the federal government nuclear labs. Light water reactors and their profitable fuel assembly rods are selling around the world. Uranium has few secrets after 70 years of experience. Regulations and security practices are in place. Thorium might rapidly disrupt this entrenched system if the playing field was level.

Milton Shaw entered the picture in the 1970s. He was a protégé of Rickover and copied his mentor's autocratic personality. Shaw was placed in charge of the nuclear developments at ORNL, and he felt that scientists were not good at making things, so they needed his dictatorial style. The relation soured, and Shaw closed funding for the follow-on LFTR. One author wrote that Shaw's unique contribution to nuclear history was killing the ORNL LFTR program. Alvin Weinberg was removed as Director of ORNL in 1977 for objecting to the direction of nuclear power development.

What LFTR Problems Must be Solved?

You can get diverse opinions by Googling subjects such as: "What Is Wrong with Thorium." Try Googling "Is Thorium A Magic Bullet for Our Energy

Problems?" George Lerner lists the following from *What is a LFTR and How Can a Reactor Be So Safe?"* [2]

1. Turbine driving temperature in a LFTR is about 700^0C compared to an LWR of 315^0C. This gives a 40% increase in Carnot efficiency. All materials seeing the higher temperature and radiation must be evaluated (and developed) at the higher temperature.
2. Regulatory agencies must get busy on LFTR
3. Graphite has a typical life of 4 years. Graphite or other moderator material must be developed for high reliability in a strong neutron flux.
4. The containment vessels and pipes use a nickel alloy Hastelloy-N alloy. This must be tested for a 40-60 year life under these higher intensity forces.
5. Pumps, valves, and heat exchangers must be tested for 40-60 year reliability.
6. A prototype should be built.
7. It a truly disruptive technology driving a spear into the LWR industry.

Let's review and expand the LFTR features: [3-5]

There is a remarkable list below that has been verified by the prototype tests, and also by the nuclear physicists and engineers who in a long historic line.

- The molten salt coolant contained at atmospheric pressure eliminates the high-pressure water and need for a super containment cover. Elimination of coolant water in a thorium reactor gets rid of the hydrogen explosion problem that occurred at Fukushima Daiichi, and the steam explosion at Chernobyl and Three Mile Island. The Three Mile Island core melt down was related to the faulty water coolant control. These three accidents disappear with the LFTR.
- The elimination of the steam or hydrogen explosion problem allows a smaller containment cover. This reduces the size of the reactor, reduces costs and construction time, and allows for an underground reactor.
- The LFTR burns 99% of the fuel with 1% waste. In contrast, the uranium Light Water Reactor (LWR) burns about 1% of the fuel with 99% waste. A LFTR produces about 10,000 times less radioactive waste than equivalent LWR waste

for the same power generated. Higher efficiency also means less heat thrown up into the atmosphere.

- The LFTR can burn the waste fuel from conventional LWRs and its own thorium reactors. This dramatically reduces the amount of waste in storage of conventional nuclear reactors and extends total fuel source by estimates of five to six hundred years. Uranium waste becomes thorium fuel.
- A pound of thorium in an LFTR generates as much power as 300 pounds of LWR uranium and 3.5 million pounds of coal [2]. Thorium is energy dense.
- Since the fuel is held in a molten state, there can be no fuel meltdown. LFTRs have another fuel safety feature. If the circulated fuel overheated, a metal drain plug melts and the fuel containment vessel is gravity drained to a receiving tank. If a fuel leak occurred, the fuel would become solid where the temperature outside the leak was less than 434 ^{o}C. A leak is self-contained.
- The LFTR has cost savings over an LWR. The piping is simpler, and the LFTR does not require the complex accident controls and high-tech security.
- An air-cooled system for smaller LFTRs does not have to locate near an ocean, lake, or river. This was demonstrated by the Chinese Gobi desert LFTR.
- The LFTR has a turbine input temperature around 700-1000 ^{o}C compared to the LWR at 315^{o}C. This is a significant improvement in the Carnot engine turbine efficiency.
- LFTR waste is worthless as a nuclear weapon material. You can’t easily make bombs from ^{233}U waste partly because of ^{232}U contamination.
- The proliferation risk is small, so the LFTR does not need the super critical police security.
- Less U is shipped to the plant since LFTRs only need a small starter amount.
- There is no complex enrichment process needed for the ^{232}Th ore. ^{232}Th is separated from the ore with sulfuric acid.
- Smaller power LFTRs can be placed below ground level increasing security and reducing footprint.
- Oak Ridge National Laboratory (ORNL) and the Idaho National Lab demonstrated two prototype molten salt reactors in 1964 and 1969 that burned ^{233}U. The first commercial nuclear reactor in Shippingport, Pennsylvania operated for five years and used thorium to make the ^{233}U [1].

- The uranium waste problem is reduced in volume by a factor of 21, and radiation waste reduction is about 10^{-4}. Figure 6 compares the quantity of material between a LWR uranium fuel with the thorium reactor.

This list seems too good to be true, but prototypes tested in the 1960s proved the concepts.

What is the World Status with Thorium (LFTR) Reactor Development?

There are several international paths to the thorium nuclear reactor. The list of 12 countries below with a short description for each is intended to illustrate the world activity for thorium reactors. Several countries express the same motivations of safer, cheaper, reduced nuclear waste, increased fuel and reactor efficiency, no water in the reactor, medical use of the Th waste, and a saleable power output allowing small reactors. These technology paths and countries include

1. One path is a US Manhattan type project with large investment. Fermi demonstrated a chain nuclear reaction on December 2, 1942, and the first atomic bomb exploded in New Mexico on July 16, 1945 [**6**]. If that project overcame immense technical challenges to produce an atomic bomb in less than three years, the LFTR project should be a cakewalk. Although, the political climate won't support this direction, it stands as a reference for what can be done.
2. China began their LFTR project in 2011 and is now a world leader. They have announced a project with 700 nuclear engineers and staff, and a billion dollar budget. They have announced that two 12 MW thorium reactors are in place in the Gobi dessert.
3. France: A major consortium research reactor is being built in France. It is funded by eight countries, the EC, and private firms. Wikipedia described it, "The Jules Horowitz Reactor is a material testing reactor, with a power output of approximately 100 megawatts. It is designed to be adaptable for a variety of research uses by nuclear utilities, nuclear steam system suppliers, nuclear fuel fabricators, research organizations and safety authorities.

4. India has a 3-phase project with target prototype scheduled for 2020. India has the 2nd largest thorium reserves in the world and very little uranium.
5. Canada has the Terrestrial Energy Corp 7-year core replacement concept. An approximate 2030 date to prototype is given. The Oak Ridge National Lab (ORNL) has a consulting contract with Canada on their LFTR development.
6. The USA has a few startup companies with Flibe Energy Corp., ThorCon Power, Martingale Inc., and U Power offering slightly different designs.
7. Japan: The Fukushima-Daiichi accident in 2011 caused Japan to cancel a reactor program modeled after the ORNL LFTR.
8. The United Kingdom has the private company Moltex Energy developing a mixed Thorium-Uranium fuel. It will produce power outputs ranging from 150 MW to 1,500 MW.
9. Norway is currently testing thorium fuel rods in existing nuclear LWR reactors. Thor Energy is pairing up with the Norwegian government. They began the 2nd phase of the project in January 2016 that is examining long-term properties of fuel. The project will investigate molten salt technology.
10. Brazil: The major contribution of Brazil is the quantity of its thorium ore and history of processing pure thorium material.
11. Turkey's place in the mix is that it has the 2nd highest amount of thorium second to India.
12. Denmark: Copenhagen Atomics sprang from a nuclear group at the Technical University of Denmark. Its initial design is for a uranium waste burner evolving to an MSR thorium reactor. Another company Seaborg Technologies began in 2014 with four founders who originated from the Niels Bohr Institute in Copenhagen.

An interesting relation is that the Oak Ridge National Lab in Tennessee is a consulting partner with China and Canada [7]. Why does an American National Lab partner with foreign developers? One reason may be that the project licensing and regulations in USA are a significant burden adding time, and these rules don't apply outside US. Martingale Inc. selected countries around the world that don't have restrictions on anything called nuclear. Thorium LFTR regulations could take 8-10 years to write. A quote from an American engineer is that "If China can solve the climate change problem, then let them do it."

Flibe Energy Corp. is using the US military as a customer to avoid the commercial regulations. Those companies who sell equipment outside the US licensing and regulations are confident of the safety of Th-reactors and cite that US rules were written for uranium LWRs.

The US National Labs have a program called a CRADA, a Cooperative Research and Development Agreement in which the Labs partner with industry in financing targeted research. The funding is typically 50-50. I worked under electronic research CRADAs at Sandia National Labs and found them stimulating and innovative. It joined the power of the government labs with industry. Both brought something different to the table.

There are several good books on thorium reactors that are listed in the references. I will mention only six sources listed in the bibliography that were especially influential. I choose them because they come from diverse and intensive backgrounds, but their conclusions are the same. My apologies to the other influential authors listed in the references. I have been asked by doubters "if thorium is so good, why haven't I heard of it before." Try these references for starters.

Robert Hargraves - He is a physicist now with Dartmouth College who has crafted a careful cost analysis of thorium reactors in the urgent future of power generation [3-5]. He spent much of his career in industry and speaks frequently on the subject of thorium power.

1. Ref: the book *Thorium: Energy Cheaper than Coal* and a good article in American Scientist, "*Liquid Fluoride Thorium Reactors*," July-August 2010.
2. James Mahaffey - He is a veteran hands-on nuclear engineer who has a gift for careful and good writing. His coining of the phrase "Rickover trap" is a good one. He brings a ton of relevant details in his book *A History of Nuclear Meltdowns and Disasters: From the Ozark Mountains to Fukushima*.
3. Kirk Sorenson - He is a veteran nuclear engineer, a forceful speaker, and a leader in establishing this thorium disruptive energy practice. Look him up on www.youtube.com and on his website www.energyfromthorium.com.

4. Mark Lynas - He is a British writer and self-professed environmentalist, who was active in the anti-nuclear protests in the 1980s and 1990s. With that enthusiasm for a cause, it was a painful journey for him to evolve into full support for nuclear power, specifically thorium. Ref: *Why a Green Future Needs Nuclear Power*.
5. George Lerner, - He is a business consultant. His book is a short summary of all the LFTR features for those of you who are short on time. Read his book *What is a LFTR, and How Can a Reactor Be So Safe*.
6. The *Economist Magazine* - "*Asgard's fire*," April 12, 2014, is a lay article in a respected publication. It covers all the thorium points.

Jim Gover, formerly of Sandia National Labs, wrote the following about the poor state of the American public position on nuclear technology.

- Misinformation, and the isolation of technology from public understanding
- The public lacks the knowledge base in energy to make informed recommendations to legislative and executive bodies of governments
- Educational institutions and news media are misinforming or, at best, under-informing students and the public on the pros and cons of energy alternatives
- Governments find it difficult to craft effective, long-term energy policies that are non-partisan. In the absence of US federal leadership in energy policy, states act independently – sometimes wisely, sometimes unwisely.

We have covered the pluses and minuses of an untapped thorium energy source. Several countries are supporting research and development of a technology heavily developed and demonstrated in America in the 1950s to 1980s. To those whose who are skeptical about thorium reactors and say "Why haven't I heard about this?" or "It seems too far-fetched to invest in another nuclear reactor", we would say, "the atomic bomb in 1938 was confidently predicted by physicists, and with only their experiments and theory, it happened exactly as they said it would." There are more physics facts and theory to go on with a LFTR reactor now than the atomic Manhattan Project had!

References

1. Alvin Weinberg, The first nuclear era, AIP Press, 1994.
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4. Robert Hargraves, Thorium: energy cheaper than coal, Amazon Digital Services Inc., 2012.
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6. Richard Rhodes, The making of the atomic bomb, Simon and Schuster.
7. Richard Martin, Fail-Safe Nuclear Power - MIT Technology Review, August 2, 2016.

Chapter 19

Thorium Reactor III

What Problems must be solved for a Thorium Reactor?

There are Internet debates that argue details of LFTR problems. Some comments are quite shallow, such as, “If LFTRs are so good, why haven’t I heard of them” or “Why aren’t they in use” or “All nuclear is bad.” But gleaning through to the more serious comments, we find that materials science studies at higher reactor temperatures and different radiation environment require prototype data.

LFTRs have a complex chemistry, and there are many designs that can be pursued. What is the best mix for the nuclear fuel soup? Where will the large amount of financing come from – the government typically steps in when the risk is too great for the private sector.

What about thorium reactor regulations? These are important, but solvable problems. The uranium regulations took years to finalize. But remember that it took 2-years and 9-months for the Manhattan Project to go from proof of concept (Fermi’s sustained nuclear reaction) at a football stadium to proof of product (the explosion of the bomb in New Mexico) [1]. What are we afraid of with a thorium reactor? We can’t wait years to develop new Th regulations. We need safety regulations, but they are now a serious impediment driving American developers to go overseas or to the military.

A list of special design techniques might include:

- Design for rapid diagnosis of failure or degraded operation
- Design for rapid repair
- Design for reliability of system, subsystems, and components
- Design for testability of system, subsystems, and components

- Design for rapid reactor assembly
- Design for safe and easy transportation
- Design for easy installment at the reactor site
- Design for easy fuel injection and withdrawal
- Design for rapid human mobility in the reactor physical space
- Design for lowest cost consistent with above goals – no compromise on quality!
- Design for decommissioning

Thorium & Uranium-233 Reactor Waste

Waste is a challenging problem for a LWR uranium reactor. But let us examine and compare the uranium waste with a thorium reactor. First, where do the waste elements in a thorium reactor come from. Thorium-232 is a fertile element, and therefore doesn't directly generate waste. Second, under slow neutron bombardment, thorium with an atomic number of 90 transmutes to fissile uranium-233 with an atomic number of 92. It is U-233 that fissions and makes the waste not thorium. Each time a U-233 cracks and splits into two fragments, the nucleus protons are conserved so that the sum of the protons in the two pieces must equal that of U-233 or 92. The first experiment by Meitner and Hahn found barium in the waste with an atomic number of 56, and the missing fragment was 36 and krypton was found immediately in an experiment by Meitner's nephew Otto Frisch.

When a U-233 atom splits, each U-233 atom can fission into a variety of fragments as long as the sum of the protons in the two fragments equals 92. Figure 1 shows the statistical distribution of the waste of a U-235 atom. The two distributions reflect that we are looking at the sum of two numbers whose sum must be 92. The typical distribution plots show atomic mass not atomic number so the sum of two pairs must be equal to 233. A low number in the distribution would link to a high number in the high distribution and so on. As an exercise, add the two lowest numbers or the two points at the bottom of the trough in failure

1 and you get 235. The point is that a fissile element creates a waste pool distribution of many different types of radioactive elements.

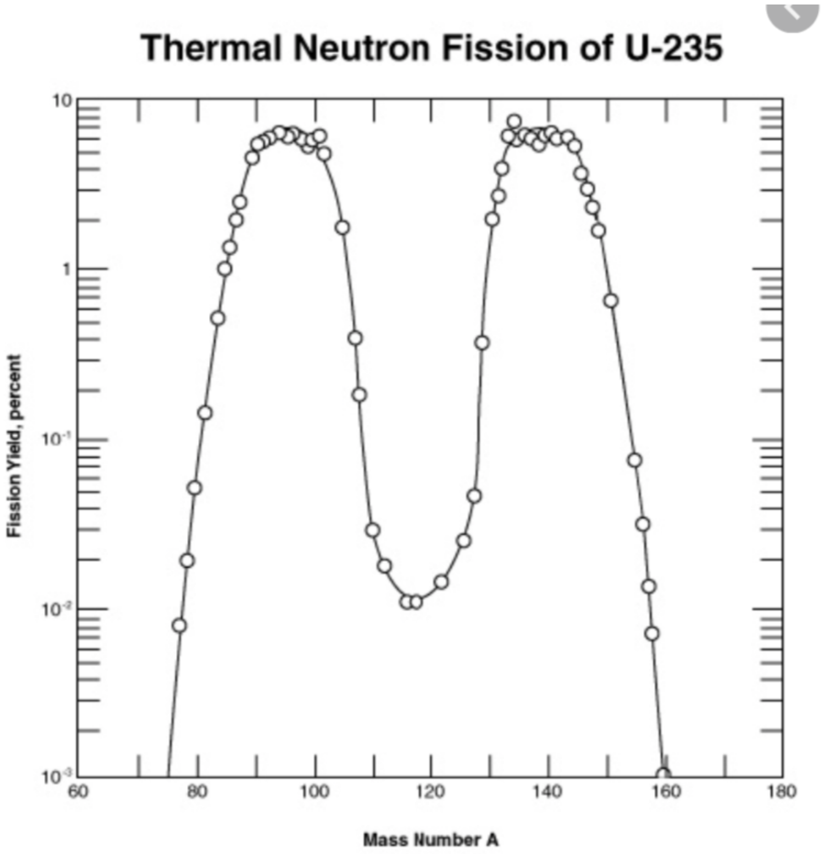

Figure 1. Yield of fission fragments as a function of atomic mass number A for thermal fission of 235U (in percent per fission).

https://www.slideshare.net/sanjokk/fission-9424055

The difference in waste mass between a thorium or a uranium LWR reactor is important. Robert Hargraves and Ralph Moir analyzed the comparison shown in Figure 2 that compares the difference in waste masses if both types of reactors generate the same power [6]. Assuming we start with 1-ton of thorium that needs no enrichment and an equivalent energy of natural uranium of 250 tons that has 35-tons of U-235 and 215-tons of depleted U-238. The 215-tons of depleted U-238 become contaminated in the fission reaction. The 35-tons of LWR U-235 is 1% burned.

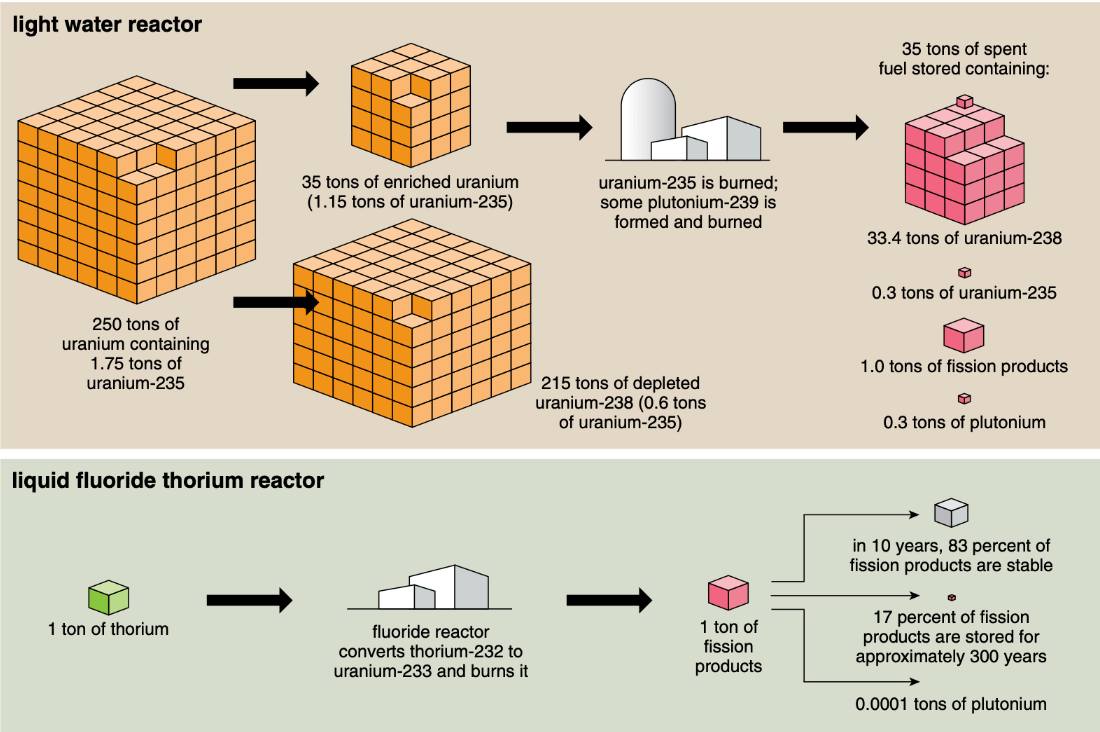

Figure 2. Compares the quantity of waste material between a LWR uranium fuel with the thorium reactor [5].

Figure 2 data compare the decay reactor waste of both elements if Th and LWR U have the same output power [5,6]. A 1-ton of thorium equates to 35-tons of enriched uranium to achieve the same output power. The uranium waste is about 35-tons, and the thorium-uranium-233 waste is only1-ton.

The 1-ton of thorium input material is close to 99% burned into ^{233}U in the reactor leaving about 1-ton of waste fission product. The mass of waste thorium is approximately 1/35 = 2.9% of the uranium waste. There is only a trace of plutonium is in the thorium-^{233}U waste, but significant plutonium and radioactivity in the uranium LWR waste. So, there is a large reduction in thorium-uranium-233 waste volume and a much lower radioactivity.

A visual equivalent is the claim that if all the US uranium nuclear waste for past 55 years was laid out on a football filed, the height of the waste would be 10 inches. If an equivalent energy of thorium was laid out on a ping pong table, the waste height would be about 1.46 cm.

Figure 3 plots the decay of radioactive uranium and thorium reactors and introduces the term actinides. Actinides refers to the collection of elements from atomic number 89 – 103. We are familiar with thorium (90), uranium (92) and plutonium (94), and maybe the smoke detector element Americium (94). All elements in the actinide cluster are radioactive, and some are found in the nuclear waste. Their half-lives range from microseconds to minutes, days, and years. Thorium reactors emits gamma rays, particle radiation, and deposit nuclear fission fragments of thorium-uranium-233. Uranium-238 waste contains significant plutonium while uranium-233 contains only a trace.

The cooling time to store the thorium - uranium-233 waste in a cask is 300 years. Cesium has a half-life of 30 years. So, to wait ten half-lives is to wait 300 years. Plutonium with a half-life of 24,000 years sets a uranium ten half-life target of 240,000 years. Some elements have half-lives in the billions of years. The immediate radiation of these long half-live elements usually is not a concern since the radiation is quite small.

The radioactive storage time reduction from uranium to thorium is a factor of 10,000 for the range from time = 0 to 300 years and even longer (Fig. 3). These overwhelming data conclude that a thorium reactor reduces the classic waste problem by orders of magnitude. Additional data show that a thorium reactor can use waste as a fuel further draining the waste problem. Thorium waste is then not a waste, but a fuel. These three strong points, smaller waste volume, lower waste radioactivity, and waste as a fuel deserve more exposure when advancing the thorium message!

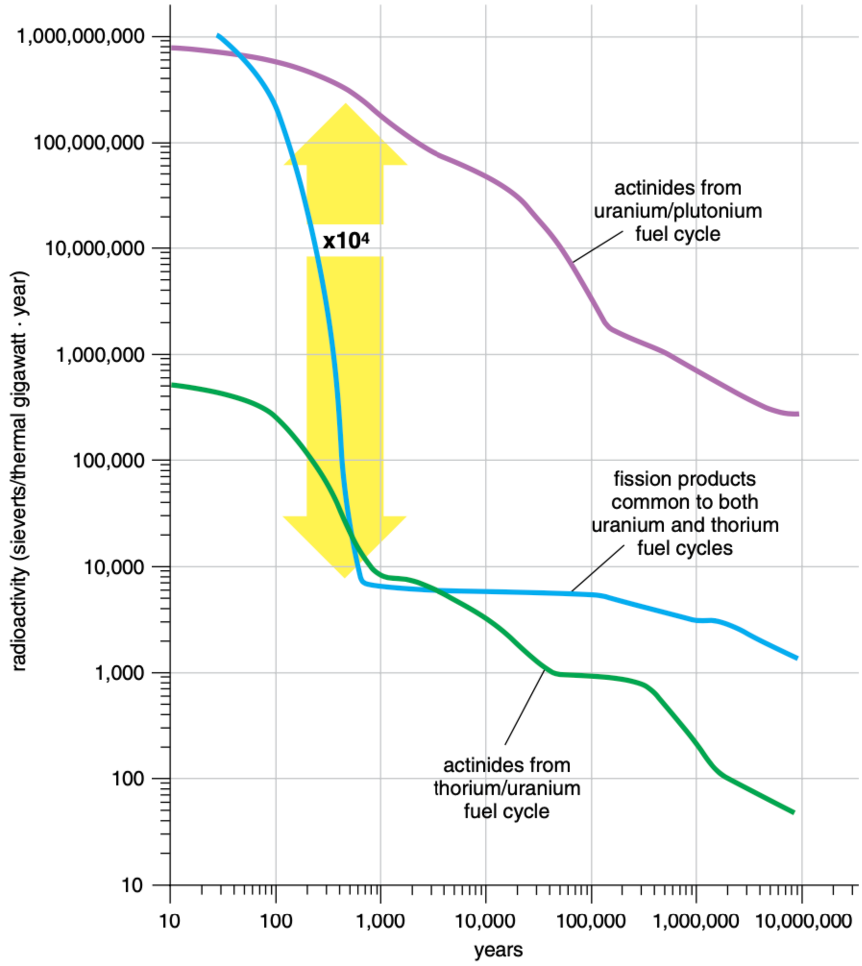

Figure 3. Robert Hargraves and Ralph Moir compare the decay time of uranium and thorium (U-233) waste [5]

T

here is one small amount of byproduct left in the molten salt fluid that poses a problem. The thorium-232 uranium-233 cycle produces a small amount of uranium-232 that has a half-life of 72 years. U-232 decays to titanium-208, and along the way a very high energy gamma ray of 2.614 keV is emitted. This requires an extra thick shield of lead, concrete or titanium shielding and remote handlers.

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Chapter 20

INTEGRAL FAST REACTOR (IFR)

The Integral Fast Reactor (IFR) has features in common with the thorium reactor. But one big difference is that the IFR uses enriched uranium. The IFR transmutes ^{238}U to ^{239}Pu, while the thorium reactor transmutes ^{232}Th to ^{233}U. These are major differences, but *both* designs burn up 99% of the fuel (1% waste), can burn waste fuel from other reactors, use a molten coolant at atmospheric pressure eliminating the high pressure water explosion problem of the popular Light Water Reactor (LWR), use helium gas instead of high pressure steam in the reactor, have proven passive shut down features in case of emergency, require lower level of security than LWRs, can operate at much higher turbine temperatures than LWRs, have high resistance to proliferation, are cheaper than LWRs, and were demonstrated with prototype reactors. Lower pressure means that pipe metal thickness can be on the order of 4-inches and not 10-inches.

Wow! 99% burn up, burns our nation's nuclear waste pile for fuel, no water explosions, passive safety shutdown, more efficient, reduced expensive security and reactor containment, and demonstrated prototypes verifying these claims. Sounds familiar. Did this just happen? No, both nuclear designs were built and tested by the late 1980s. We will describe the IFR, and then compare the thorium and IFR products. Which one is better, or do they both have a place? The end result has promise to solve the world's energy needs for centuries and eliminate our nuclear waste and safety problems.

Charles E. Till and Yoon Il Chang are physicists whose long careers at the Argonne National Lab (ANL) spanned the history of the IFR [1]. Their book is the best on this topic. It is "*Plentiful Energy: The Story of the Integral Fast Reactor*." The story covers the history of ANL and the technology leading to two successful Experimental Fast Breeder Reactors, the EBR-I and EBR-II (Fig. 1). The EBR-II was converted to an IFR in 1984 and ran successfully until 1994 (Fig. 1).

Figure 1. The Experimental Breeder Reactor (EBR-II) at its test site at the Idaho Argonne National Lab West now known as the Idaho National Lab. The EBR-II ran for 30 years and as an IFR the last ten years. On April 3, 1986, two tests demonstrated the inherent safety of the IFR concept. These tests simulated accidents involving loss of coolant flow. Even with its normal shutdown devices disabled, the reactor shut itself down safely without overheating anywhere in the system. (From Wikipedia)

The EBR-II converted ^{238}U to ^{239}Pu. When high-speed (fast) neutrons are fired at the nucleus of ^{238}U, a transmutation result is fissile ^{239}Pu. The high-speed neutrons ejected from the Pu fission keep the chain reaction going. The non-fuel, the *fertile* uranium-238, is said to *breed* the *fission* fuel plutonium. The fissioning ^{239}Pu creates the heat to drive steam or gas generators. The IFR uranium fuel is actually a liquid metal alloy of uranium-plutonium-zirconium, and the uranium fuel must be enriched to 20-25%.

The IFR breeder works if the neutrons have high velocity, while the thorium reactor works if neutrons are slow. Fast neutrons travel about one-fifth the speed of light while the thermal neutrons travel at a relatively slow 2200 m/s.

The EBR-II integral fast reactor used a liquid sodium coolant that melts at 98.7 ^{o}C and boils at 883 ^{o}C (Fig.1). This allowed the coolant to operate at atmospheric pressure eliminating the water explosion problem of LWRs. Sodium does not react with uranium, but a safety concern is that it reacts *violently* with water although not so violently with air. The Na coolant has better thermal properties than water for this purpose.

The IFR (and LFTR) can burn waste fissile material from its own or other reactors. This is a huge positive factor. The IFR uses a complex recycling process called pyroprocessing that can be co-located with a reactor (Fig. 2). The lower half of Fig. 2 show the liquid fuel circulating through the pyroprocessing that separates out toxins and recycles unburned fuel. This continuous filtering allows the reactor to burn up 99% of the initial fuel.

E-Hitachi has proposed a PRISM IFR reactor to the British government. If the government will support development of the PRISM IFR, then the huge British stockpile of plutonium can be slowly reduced while fueling electric power at the same time. If approved, the bid decision targets a reactor in about 2025. It is ironic that the IFR developed and tested by the US is now bid to a foreign country for commercial financing.

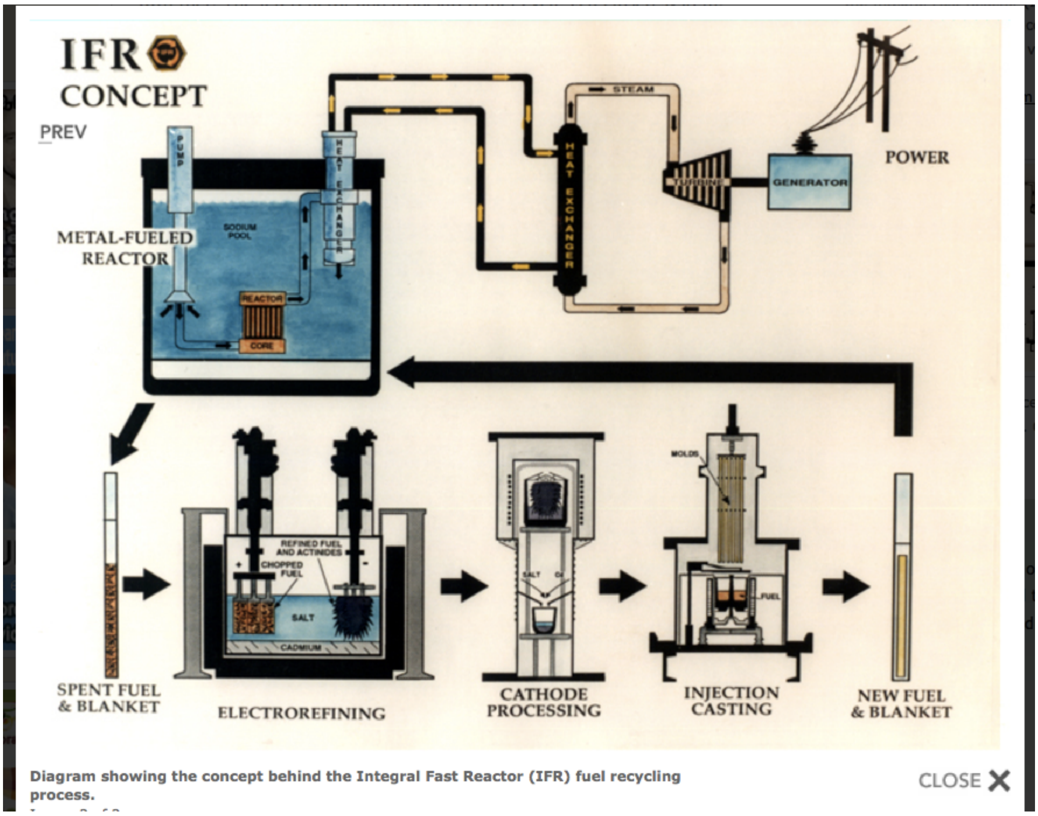

Figure 2. Flow diagram of IFR (from Argonne National Lab, http://www.ne.anl.gov.)

Why Did the IFR Development Effectively Die in 1994?

There are four plausible reasons. One is that the Clinton-Gore Administration was beholden to the anti-nuclear environmental lobby for its support in the 1992 election. ANL was ordered to dismantle the IFR program. Another reason cited is that the uranium Light Water Reactor industrial forces were too strong to let a newcomer take over. Two technical reasons cited were that the sodium coolant is explosive in contact with water, and the fear of nuclear proliferation. Despite weaknesses with the LWRs, worldwide manufacturing and LWR business is strong. Financial backing for IFRs is difficult.

The US may have slowed its IFR development, but this did not affect the IFR work in countries around the world. Russia, China, India, Japan, England, and France are actively pursuing IFRs. The GE-Hitachi IFR funding proposal to Great Britain illustrates the corner that the US has trapped itself into.

Anti-nuclear environmental groups had a strong influence on retarding anything with the word “nuclear” on it. The Sierra Club and Greenpeace International do good work in some areas such as stopping new coal fired plants, but retarding nuclear energy is not one of their positive contributions to solving the baseload energy and climate challenges.

How do We Decide Between a LFTR and an IFR?

Both reactor designs have impressive properties. So, how do we choose? The biggest difference is the LFTR thorium-uranium basis versus the IFR uranium-plutonium basis. Uranium is mined and must be enriched to 20%-25% in the IFR, and only 0.7% of the original uranium ore is radioactive. Thorium is not radioactive with its half-life of 4.3 billion years , and does not need enrichment, which are too big advantages. Thorium is also about 4 times more plentiful in the Earth’s crust than uranium. But a thorium reactor needs a small amount of neutron source fissile starter material of ^{233}U, ^{235}U, or ^{239}Pu.

IFR advocates have made the point that the present nuclear industry in entirely uranium focused, so it is easier to convert to a new reactor design within the same fuel source than to change fuel source and design. There is probably some truth here, but we don’t know the numbers, and should it be the deciding factor? The IFR PRISM design is targeted for completion about 2025. The Chinese and the Canadian Terrestrial Energy Corp. project prototype LFTRs a couple of years later.

These LFTR and IFR designs are dramatically better than the current dominant Generation-II and –III LWR reactors. A few Generation-III designs are entering the market. They have improved passive safety features, but none have the ability to consume nuclear waste or use lower atmospheric pressure coolant. If you

Google "LFTR versus IFR" you will get a good discussion on the issues. Here is a summary of some diverse opinions from the experts.

- "I think we must pursue the final stages of research, development, and commercial-scale deployment of all of these next-generation fission technologies, since it would require such a trivial input compared to the huge investment that will be required anyway in energy infrastructure over the next few decades" (*More than $26 trillion globally by 2030*). (Barry W. Brook, http://www.bravenewclimate.com)

- "If the current perceived urgency is to sequester plutonium to put it out of the reach of proliferators, that can be done much faster with early deployment of IFRs rather than by later deployment of thorium reactors — and each IFR will sequester 8 – 10 times as much plutonium (Pu) per GWe as a thorium reactor." (George S. Stanford, www.bravenewclimate.com)

- "Thorium reactors operate with a thermal spectrum, which allows them to use graphite as the primary structural material in the reactor core. Graphite can be heated to very high temperatures without losing structural integrity. Combined with the very high boiling temperature of the fluoride-salt coolant (> 1400°C), thorium reactors can deliver heat at substantially higher temperature (between 600°C and 700°C with current primary pressure boundary structural materials) than IFR (between 370°C and 510°C with current fuel cladding materials)." (Per Peterson, http://www.bravenewclimate.com).

- LFTR is better than IFR because: It is a better coolant, * It has a chemically stable liquid salt instead of liquid sodium which reacts violently with water or air, * higher heat capacity, * 1/5th the fissile load per megawatt, * Liquid fuel, * fuel integrity cannot be damaged by radiation and not subject to fatigue or pressure failure, * fuel allows continuous removal of xenon so no startup transient poison, * suitable for continuous online reprocessing for fission product removal, * safer, * minimal geometric configuration, so cannot become super critical through an accidental reconfiguration, * already fully moderated, so cannot become super critical through accidental moderation (like core becoming physically close to materials containing hydrogen such as concrete or water during an overheat meltdown accident), * can be designed with no excess reactivity and continuous online refueling, * thermal spectrum operation makes it much easier to control as all operation is below nuclear resonances, * burning Th-232 produces ~1% of the long-lived higher actinide waste compared to burning U-238 (the fertile fuel starts with 6 fewer heavy nucleotides), * lower breeding ratio so easier to control the proliferation of reactor operators by controlling access to startup fissile material. (Chris Uhlik, http://www.bravenewclimate.com).

- IFR is better than LFTR because:, * has been much more thoroughly studied and funded, * burns U-238 which is very widely stockpiled, * burns spent PWR fuel which would be nice to get rid of, * high theoretical breeding ratio (1.8 vs. 1.3) so more reactors can be started up faster — this was true, but now the world has so much stockpiled bomb plutonium that this may no longer be a practical limitation, * U-238 is more available from seawater than Th-232. (Chris Uhlik, http://www.bravenewclimate.com).

- "While the IFR shares some of the advantages of the LFTR, the LFTR is safer and the LFTR does not require a chemical separation processing facility in order to close the breeding cycle. Thus, the operating cost of the LFTR would be significantly less than the cost of operating the IFR. Indeed, I suspect that the R&D costs of bringing the LFTR to serial production will be lower that the R&D costs of developing the IFR to serial production. R&D spending on the IFR exceeding R&D spending on MSR technology by a ratio of over 20 to 1, and arguably MSR/LFTR R&D is closer to producing a commercial product, than LMFBR/IFR R&D. (Charles Barton, www.http://www.bravenewclimate.com)
- Finally because of its simplicity, modest materials, input, and limited labor requirements, the LFTR can be factory produced at a fraction of the price of IFRs.

Some of these statements conflict or are at odds with data, but this list is representative of the IFTR versus IFR debate. Generally, the participants are not as combative as those in the other energy technologies.

Although substantial LFTR and IFR prototype demonstrations were built and tested, the issues are not settled. Is one design better than the other, or does each have its own appropriate niche? The advantages over existing systems are worth investment in research and development to decide quickly.

Reference

1. Charles E. Till and Yoon IL Chang, Plentiful energy, the story of the Integral Fast Reactor, Copyright Till and Chang, 2011.

Chapter 21
Fusion

Fusion occurs when two light elements merge their nucleus under severe pressure and heat to become another element. The atomic number of the new element is the sum of the two merging atoms. All elements lighter than iron-56 (Fe) have demonstrated fusion in the lab for short periods. The unsolved problem is to get a sustained fusion.

Nucleus protons have a strong nuclear force that overcomes an extreme electric force of repulsion between them. But if another proton or neutron comes within less than 10^{-15} m (1 fm) of another proton or neutron, then the strong nuclear force grabs the neutron or proton overcoming the electrostatic force. This distance is about the diameter of a proton or neutron. Fusion requires a large input energy to overcome the electrostatic repulsion, called the *Coulomb barrier*. When fusion occurs, about 10 times that input energy is released for power generation. Sustained fusion requires temperatures on the order of 150 million degrees Kelvin and pressures of about 10^{11} atmospheres. This is this the steady environment that the Sun enjoys.

There is a serious materials problem at these environments. There are two approaches to a fusion reactor. An international sponsored project is active near Grenoble, France using *magnetic confinement* of the plasma to keep plasma particles from touching the reactor surface. The other approach is called *inertial confinement*. It uses a small pellet that is bombarded with intense lasers or other EM energy to achieve fusion conditions. Multiple labs in the US are exploring this method.

There are many low weight elements for a fusion reactor, but the most efficient one uses the isotopes of hydrogen; tritium and deuterium. Figure 1 illustrates this fusion reaction. The chemical reaction is

$$H^3 + H^2 \Rightarrow He^4 + n + 17.6 \text{ MeV}$$

The fusion fuel uses two isotopes of hydrogen. The output is He, neutrons, and energy. The energy is heat in the form of higher kinetic energy of the He^4 atoms and neutrons. This may seem like a theoretical projection, but experiments have demonstrated fusion. And the biggest Earth demonstration of fusion was the hydrogen bomb that was exploded in 1952. The H-bomb used a fission bomb as a trigger to reach the temperature and pressure required for subsequent fusion. The fireball diameter was about four miles. Finally, fusion of two hydrogen atoms to make helium is the source of the Sun's energy.

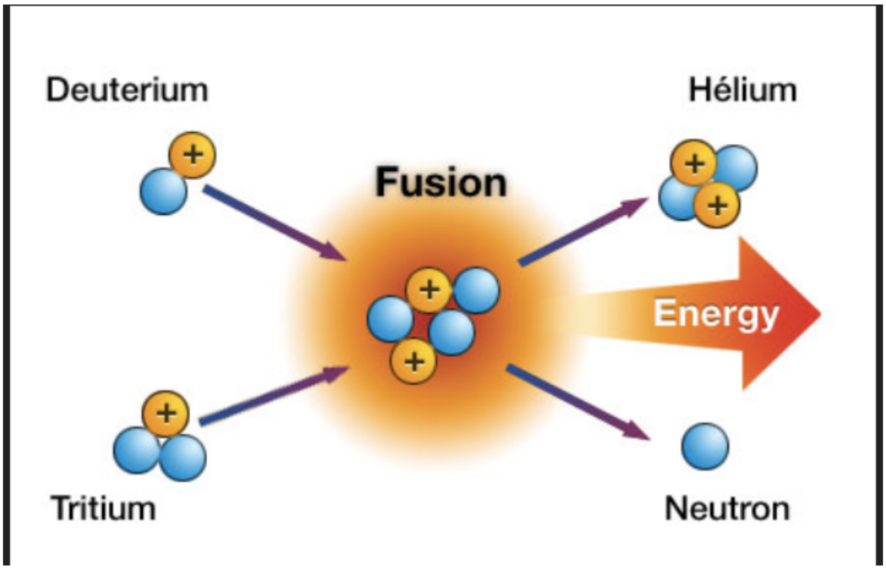

Figure 1. Schematic of fusion reaction of deuterium and tritium. (www.iter.org)

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Here are six advantages of fusion reactors

- Fusion power plants could provide reliable 24/7 electricity.
- It is energy efficient. 1 kg of fuel can generate the equivalent of 10^8 kg of fossil fuel.
- The fusion fuels are deuterium and tritium. These are easily obtained by extracting deuterium from seawater and tritium from lithium. Future fusion plants must breed tritium. Lithium is abundant in the earth's crust so that fusion fuel should last thousands of years, or more.

- There are no toxins or greenhouse gas emissions. A small amount of non-reactive helium is emitted but poses no life threat. Tritium is a concern. Tritium is radioactive, but has a short half-life, and it is cycled out of the human body as water. The latest fusion reactor designs are looking at full containment of tritium.
- The main radioactive waste comes from equipment as it absorbs neutrons and other radiation. The large flux of high-energy neutrons in a reactor will make the structural equipment radioactive. The equipment is more easily handled than conventional nuclear waste.
- Fusion reactors use a very small amount of fuel preventing a nuclear accident.

The Present and Future of Fusion Reactors A working commercial fusion reactor may be 20-30 years off, but a brief look at the principles can help us appreciate the progress and future challenges. And, fusion reactors are making progress (www.efds.org).

In 1955, John Lawson a British engineer and physicist identified the three quantities that power a fusion reaction, and they are known as Lawson's three criteria

[https://www.euro-fusion.org/2013/02/triple-product/]

These quantities are:

1. (n) the plasma particle density in numbers of particles per unit volume
2. (T) the plasma temperature in Kelvin
3. (t) the time that the reactants must be contained before escaping. Their triple product

$$TP = T\,n\,t \quad (\text{m}^{-3}\text{ s keV})$$

TP is the figure of merit that assesses the progress toward a final fusion reactor. Lawson calculated that a final reactor would have $TP = 5\text{x}10^{21}$ (m^{-3} s keV). The Joint European Torus project has reached values over 10^{21} about 1/5 of the goal. In perspective, the TP has increased about 10^4 in the past 30 years. The next generation fusion reactor goal is that the input power will be 50 MW, and the power output will be 500 MW.

The three variables have a basis in the reaction. A fusion reaction requires a dense plasma particle concentration to enhance the probability of collisions. The density (*n*) is in particle count not mass. Increased pressure increases density. Temperature is a measure of the velocity or kinetic energy of the plasma. It takes a high velocity to overcome the Coulomb barrier. A large containment time allows time for the reaction to occur. If *t* is small, then plasma escapes before it fuses.

The ITER (International Thermonuclear Experimental Reactor) group was formed in 1985 to advance fusion energy development. It has support from France, Russia, the US, the European Union, the People's Republic of China, the Republic of Korea in 2003, and India in 2005. ITER has a staff of 500 people and 350 contractors. A fusion reactor is being built in Cadarache near Marseille, France. The platform was started in 2010 (Fig. 2).

Figure 2. The fusion reactor construction in Cadarache, France.

Temperature and pressure levels will use magnetic confinement, and the reactor of choice is called the Tokamak. This is a large Russian device from the 1950s that is currently the instrument of choice. Figure 3 show an ITER Tokamak cross section. The large size of the ITER Tokamak is designed to increase the containment (*t*) to allow sustained fusion power for the first time. ITER is an experiment that is expected to demonstrate the creation and control of a burning plasma in a Tokamak.

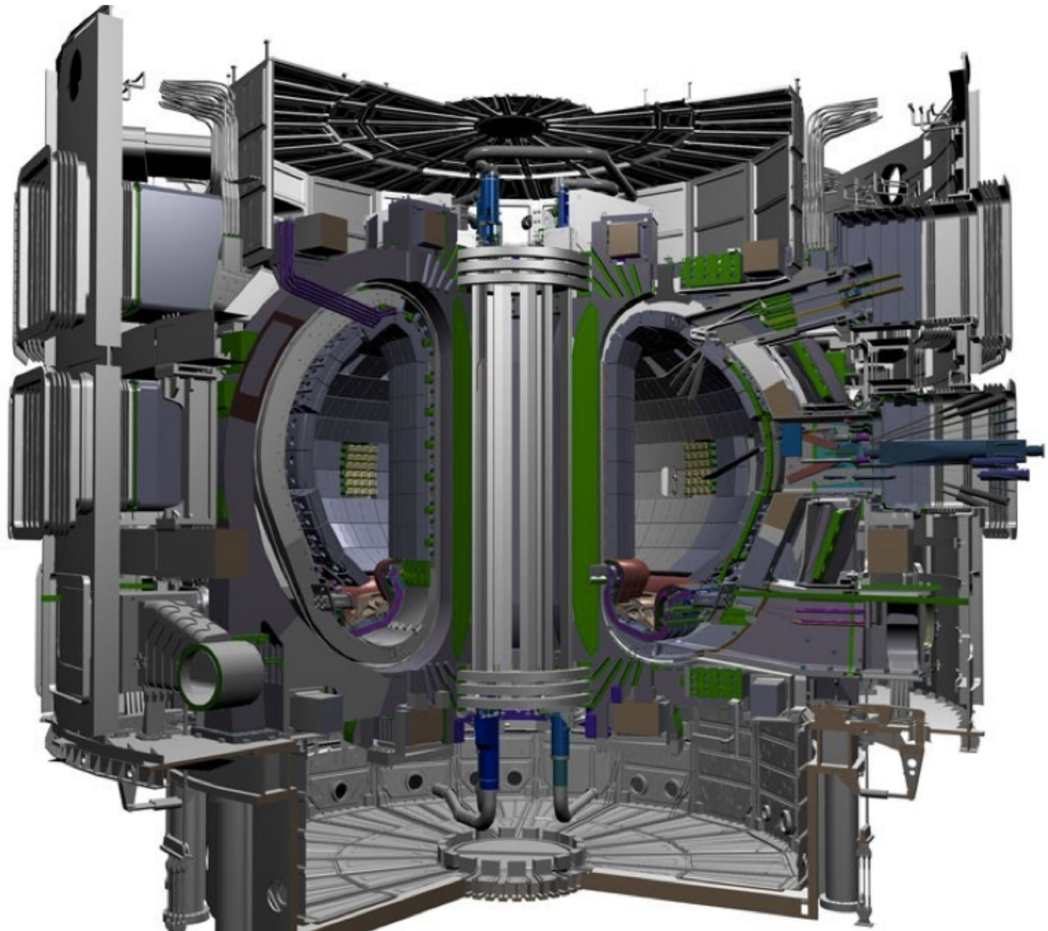

Figure 3. An ITER projected Tokamak magnetic confinement instrument. The Tokamak weighs 23,000 tons is 80 m high and has a plasma volume of 840 m^3. The fuel is a mixture of deuterium and tritium and is heated to temperatures in excess of 150 million °C, forming a hot plasma. Strong magnetic fields keep the plasma away from the walls. (www.iter.org)

The ITER project has the following target dates

- 2015 Start Tokamak assembly
- 2019 Complete Tokamak assembly, begin commissioning
- 2020 First plasma
- 2027 Start deuterium-tritium operation

We have looked at three next generation nuclear designs. They all share impressive goals. The fusion reactor seems the furthest out in time, but all three have demonstrated a high possibility of success and appear worthy of government support.

Chapter 22

What the Data Tell Us

This section condenses previous information and compares coal, gas, and nuclear power sources. Oil is not included as it is generally accepted as a non-desirable fuel source except in isolated environments. Nuclear evaluation will reference the current popular LWR, and a second nuclear comparison evaluates thorium, IFR, and fusion. For clarity, the data are spread out in a few simple tables instead of one large table. Many entrees are qualitative, and that is the nature of these wide technologies. But when marked differences exist, we can draw conclusions.

Table 1 compares CO_2, toxins, fatalities, and waste with nuclear showing superiority in greenhouse and toxic emissions, and fatalities. CO_2 emissions are huge in coal and natural gas, and coal toxins are the source of the tens of thousands of premature deaths. Mine accidents and sickness have intolerable levels for coal and gas. The Solid Waste column shows that LWR nuclear and coal are the worst choices. Coal slag contains many undesirable trace elements such as mercury, sulfur, lead, and uranium. The coal slag total volume is immensely larger than nuclear waste.

Data in Table 2 are also taken from the US Energy Information Agency (EIA). Many variables affect the cost to repair. Coal must include the railroad system and slag river spills. The nuclear reliability problem for cost of repair for plants older than 30 years are prominent negatives. Mark Cooper analyzed the large repair cost for nuclear reactors [1]. Removing and replacing a containment structure is time consuming and expensive.

Table 1. Coal, Natural Gas, and LWR Nuclear Comparison. (US Energy Information Agency (EIA)

s	CO_2 emission pounds per MW•hr (IEA.org)	Toxins	Latent Fatalities per year In USA	Mine Related Fatalities per year	Solid Waste	Public Perception
Coal	2,160	400 plants in 46 states spew 386,000 tons of 84 hazardous air pollutants.	10,000 – 30,000	1500	≈ 10% slag Contaminated fly ash is scrubbed	Neutral, but increasingly negative
Gas	1220	Traces of SO_2 and NOx	0	200	0	Favorable
Nuclear LWR	0	0	0	One fatality in last 12 years	99% long term radioactive waste	Negative

Table 2 rates the construction cost in dollars per gigawatt. These are approximate since different designs have different costs. Bernard Cohen detailed the cost to build nuclear plants [2]. Much of the costs relate to strict safety regulations. Is there a basis for coal to have a radioactive emission requirement that is three times that of nuclear? Why aren't frivolous lawsuits a part of coal and gas construction? Neither the lethality of coal nor the weaknesses of gas and oil fracking are in the public conscience - yet!

Table 2. Coal, Natural Gas, and LWR Nuclear Comparison.

	Cost to repair ($)	**Cost to Build ($$ per giga Watt)**	**Security Required**	**Reliability**	**Capacity Factor (%)**	**Emissions**
Coal	Medium	4 - 5 billion	Medium	Good	50 - 75	Bad Toxins and CO_2
Gas	Lower	2 billion	Medium	Good	35 - 65	Bad CO_2
Nuclear LWR	Billions	6-20 billion	High	not good when >30 yr.	75 - 98	Good; No emissions

Real reliability data for any energy plant should emphasize mean-time-to-failure. The capacity factor is the percentage of time that the power source is not down is often used as a reliability metric. Although capacity decreases with down time due to reliability failures (such as the recent nuclear old age shutdowns), it does account for the down time of refueling and maintenance which are not reliability failures. Reliability failures include those mechanisms that degrade but don't cause total shutdown. A capacity factor of 100% is seldom reached for any energy source. Nuclear has a better up time than coal or gas. Nuclear started at about 55% in the 1980s, and then climbed to above 90%. Recently, overall nuclear capacity numbers are dropping due to 30 year reliability problems.

Table 3 shows a major weakness of solar and wind farms to achieve a 10 GW baseload power delivery. The construction footprints are large, and the on-time capacity factor is small. The footprint in Table 3 is the final construction area of an equivalent 10 GW power source. Solar sources may scale nicely to homes and large parking lots but require enormous land area to power to a large, populated state such as Florida, California or most states.

Table 3. Nameplate LWR Nuclear vs. Solar/wind Footprint. Srukumar Bannerjee, TEAC8, 2017

	Capacity Factor (%)	**Footprint (sq km) for 10 GW generator***
Nuclear LWR	90%	2
Solar Farm	15-25%	400
On Shore Wind Farm	25-40 %	5,000

Another comparison looks at the government subsidies shown in Table 4. The lopsided numbers reflect the well-meaning desire to stimulate renewable energies. We note the absence of advanced nuclear in Table 4. Renewable energies are costly, but the real cost of subsidies is not felt by consumers when the support is hidden. A reminder is that we like renewables but know their limits. Thorium is not free, but its cost when small modular reactors are mass produced is “small” compared to uranium LWRs.

Table 4. Energy subsidies. (Energy Information Administration)

	$ per MWH
Natural Gas	0.64
Coal	0.64
Hydroelectric	0.82
LWR Nuclear	3.14
Wind	56.29
Solar	775.64
Thorium or IFR Advanced Nuclear	Small < 0.64

Figure 1 shows capacity seasonal variation data for several sources over a 34-month period in 2011-2013. Air conditioning is a major driver for summer month energy. Down time varies with season. Nuclear dips in the fall and spring due to shut down for scheduled refueling. Capacity Factors are from the US Energy Information Agency (EIA).

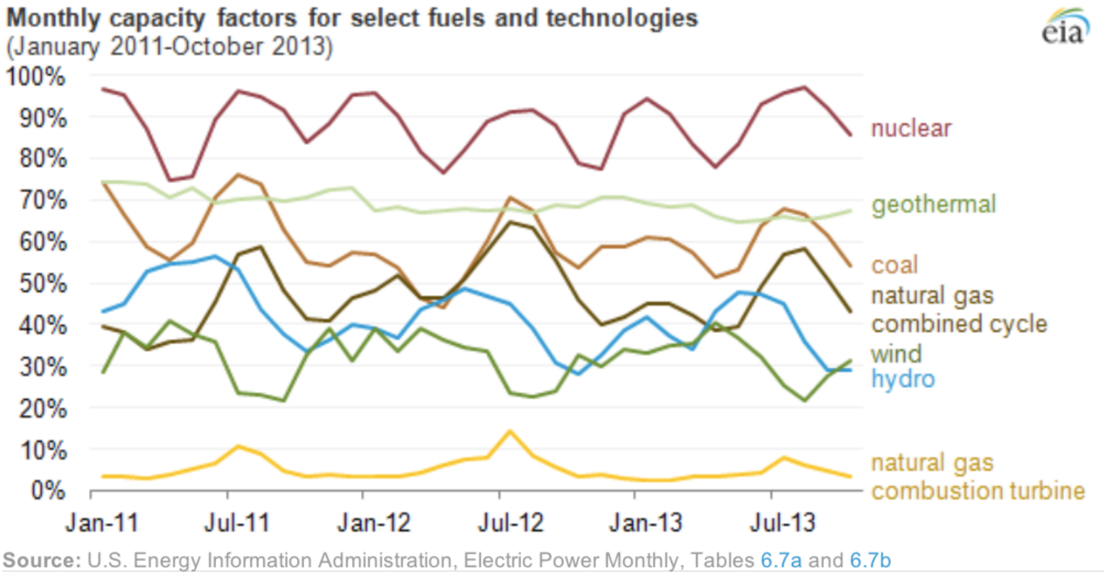

Figure 1. Capacity factors over several months for different energy sources. (www.eia.gov)

Table 5 shows environmental problems for three baseload energy sources that include strip mining, fracking, and nuclear accidents. Coal transport by rail is slow, hazardous, and prone to failure of the heavily loaded coal cars with 24/7 usage. Gas has serious methane leakage problems. The advance in efficiency is the coupled gas turbine to the steam generator that almost doubles the efficiency of single source steam generators. All sources rely on the Carnot heat engine efficiency.

Table 5. Coal, Natural Gas, and Nuclear Comparison.

	Environmental	**Fuel Transportation**	**Vulnerable to Attack**	**Passive Safety**	**Fuel Burn up**
Coal	Strip mining, and polluted air	Poor (Train)	Yes	Yes	Good
Gas	Fracking footprint and earthquakes	Medium (Pipeline)	medium	Yes	Best (100%)
Nuclear LWR	Major Accidents	Good (Truck)	Minimal	Some on latest LWR	Poor (1%)

Coal is vulnerable to attack during fuel transportation. Blowing up RR bridges can seriously disrupt coal delivery, and individual plants have minimal security. Gas pipelines could be blown up and serious if in a populated area. Nuclear plants use high tech security and are relatively invulnerable to an aircraft crash. Passive safety refers to automatic shutdown in a major accident.

Let us evaluate the three advanced nuclear designs in Table 6: the thorium LFTR, integral fast reactors, and fusion. Thorium and IFR score high on all five columns. Although fusion has many attributes, it doesn't compare well on the issues of burning uranium nuclear waste, no demonstrated prototype for sustained operation, and it has a longer projected time frame for a prototype.

Table 6. Thorium, Integral Fast Reactor, and Fusion.

	Fuel Burn up	**Burn nuclear waste as fuel**	**Proof of Concept**	**Estimated Next Prototype**	**Water Explosion**
Thorium	99%	Yes	Yes	2020	No
IFR	99%	Yes	Yes	2025	No
Fusion	100 %	No	Limited	2030	No

Table 7. Thorium, Integral Fast Reactor, and Fusion.

	Fertile Fuel Radioactive	**Need High Security?**	**Passive Safety**	**Mining**
Thorium	No	No	Yes	Safe and Abundant
IFR	No	No	Yes	Natural uranium ore enriched to 20%
Fusion	Needs tritium and deuterium	No	Yes	No mining

All three advanced designs score well in Table 7 except the last column. This may be a differentiator between Th and U. Natural uranium must be enriched to 20% IFRs. Thorium is not radioactive and natural uranium-235 is. The ore processing is minor for Th compared to U. And Th is 4 times more abundant than U. An issue is the uranium industry experience and comfort with the LWR.

Table 8 shows no water needs for the reactors. Nuclear proliferation faces a complex nuclear chemistry mix and intense radioactivity of the fuel. Lithium and water have been suggested as fusion reactor coolants (TBD) [3].

Table 8. Thorium, Integral Fast Reactor, and Fusion.

	Reactor Water Needs	**Proliferation Resistant**	**Coolant**	**Public Perception**
Thorium	None	Yes	Molten salt	Antinuclear
IFR	None	Yes	Gas	Antinuclear
Fusion	None	Yes	TBD	none

The US Energy Information Agency (EIA) published capacity factor data comparing the percentage of time that the many energy sources actually deliver power in a year. Table 9 evaluates energy sources from a different angle. For example, nuclear supplies about 20% of our total power, but it has an up time of about 92%. In contrast, coal once supplied about 62% of our total power, but has an uptime of about 56%.

Wind and solar capacity averaged over the five years from 2013 to 2017 are respectively about 34% and 27%. We could say that if a community has a low wind capability, then it might use solar renewables. Then on average, a baseload energy would need to supply 73%. It is more complicated than that. The 27% solar comes from a good solar site in the high desert, sunny country of New Mexico.

Table 9. Comparative capacity factors on energy source (2017).

Year	Non-fossil fuels							
	Nuclear	Conv. Hydro	Wind	Solar PV	Solar CSP	Landfill Gas and MSW	Other Biomass including Wood	Geothermal
2013	89.9%	38.9%	32.4%	NA	NA	68.9%	56.7%	73.6%
2014	91.7%	37.3%	34.0%	25.9%	19.8%	68.9%	58.9%	74.0%
2015	92.3%	35.8%	32.2%	25.8%	22.1%	68.7%	55.3%	74.3%
2016	92.3%	38.2%	34.5%	25.1%	22.2%	69.7%	55.6%	73.9%
2017	92.2%	45.2%	36.7%	27.0%	21.8%	70.9%	50.7%	76.4%

Coal	Natural Gas				Petroleum Liquids		
	CC	CT	ST	ICE	ST	CT	ICE
59.8%	48.2%	4.9%	10.6%	6.1%	12.1%	0.8%	2.2%
61.1%	48.3%	5.2%	10.4%	8.5%	12.5%	1.1%	1.4%
54.7%	55.9%	6.9%	11.5%	8.9%	13.3%	1.1%	2.2%
53.3%	55.5%	8.3%	12.4%	9.6%	11.5%	1.1%	2.6%
53.5%	54.8%	9.4%	11.3%	NA	13.0%	2.0%	NA

- CC = Natural Gas Fired Combined Cycle
- CT = Natural Gas Fired Combustion Turbine
- ST = Steam Turbine

- ICE = Internal Combustion Engine
- ST = Steam Turbine
- CT = Petroleum Liquids Fired Combustion Turbine
- ICE = Internal Combustion Engine

Renewables can off load the burning of fossil fuels during peak generation. But renewables have a place in our current system when we look at the cost in human health and fatalities of fossil fuels. The larger solar farms typically cost about $2 million per Megawatt. Renewables are an expensive supplement. Thorium molten salt rectors as a baseload bypass these renewable hurdles.

David MacKay wrote Sustainable Energy - Without the Hot Air that quantified the relation between various renewable energy sources and their ability to replace baseloads [4]. MacKay's quantified conclusions are consistent with those in this book.

A report from the MIT Technology Review by noted author Richard Martin discussed the Chinese thorium project in more detail (August 2, 2016). The Terrestrial Energy Corp. with partial Canadian funding uses the same estimate of 2030. Those are the new numbers. Their projections use a stepwise design approach to solve significant materials challenges. Both efforts have had consulting contracts with the nuclear reactor group at the Oak Ridge National Lab.

https://www.technologyreview.com/s/602051/fail-safe-nuclear-power/

The Short Argument for Thorium

The evidence for a small modular thorium or IFR molten salt reactor is strong, but at some point, a person must commit to the concept. All of the thorium positive features are wonderful, but if you are not a nuclear engineer close to the work, how do you have confidence in your decision. I will share the short list of why I crossed the line. There are several excellent references, but my short list cites people, energy institutions, and countries.

- The Edward Teller and Ralph Moir paper in 2005 on the small molten salt modular thorium reactor [6]
- The hardware proof of concept with ten years of ORNL development, and the testing in the Idaho National Lab and commercial Shippingport power plant
- The talks and papers from John Kutsch, Kirk Sorensen, and Robert Hargraves and his book.
- The public presentation by Jiang Mianheng, the Director of the Chinese Academy of Science of a well-funded thorium project with 700 Chinese including a consulting contract with the Oak Ridge National Lab

- The work and publications of Alvin Weinberg

Edward Teller was in the center of the Manhattan atomic bomb project. During the early 1940s, he and Enrico Fermi conceived of a hydrogen bomb before the atomic bomb was even demonstrated. And based on the physics an H-Bomb was exploded in 1952. Without arguing the debate over nuclear weapons, the point is that one of the premiere nuclear physicists in the world supported a thorium reactor with a 7-page description. Ralph Moir is a highly regarded nuclear physicist. Google Teller and Moir for the paper.

Kirk Sorensen and Robert Hargraves and others have studied and presented their analysis in open discussions. The Hargraves book is a thoughtful study of the thorium small reactor concept with a detailed economic analysis [5].

Alvin Weinberg was Director of the Oak Ridge National Lab who used the power of the ORNL to explore different reactor designs most importantly the thorium reactor. He held the patent on the LWR high pressure design, and taught Rickover the essence of the LWR design used in the *Nautilus* submarine. His papers and books support his authenticity.

The 1940s Manhattan project overcame huge technical obstacles, especially in nuclear chemistry and in materials science to achieve a nuclear energy explosion in a short time. That is relevant to the materials science challenges of designing a 40-60 year thorium reactor. Only China and India have large scale government funded thorium reactor projects. The smaller startup companies are good, but they don't have the financing or power of the US government nuclear labs. China recently announced success of a 2 MW thorium MSR with higher power reactors in development (John Kutsch, Thorium Energy Alliance).

It is important to include those that I don't believe in the thorium debates. These include

- The fossil fuel industry advertising and video tutorials
- The LWR manufacturing industry
- The anti-science politicians
- The nuclear fear propagators such as Greenpeace International and the Sierra Club (with whom I was once an active member)

- The US Government provides good nuclear data, but energy spokes persons often appear linked to the interests of some of the industries, such as the use of the Linear No Threshold (LNT) model for radiation mortality weakens its voice.

Bloomberg News reported a 246-page MIT Report on September 03, 2018, titled "Power Isn't Cheap but Can Help Climate Crisis." A major conclusion is that "Deep De-Carbonization Needs Nuclear." The report reads "As of today and for decades to come, the main value of nuclear energy lies in its potential contribution to de-carbonizing the power sector. Cost is the main barrier to realizing this value. Without cost reductions, nuclear energy will not play a significant role."

Adam Higginbotham wrote in scathing comments about the horror of the Chernobyl accident in *Midnight in Chernobyl* [8]. As I read, I expected a closing with negative comments about using anything nuclear. Not so. He closed with arguments that climate change control can only happen with nuclear energy. He concluded with an endorsement of the 4th generation nuclear designs specifically mentioning thorium reactors.

A qualitative evaluation of energy sources leads us to

Th > IFR >> LWR-BWR >>> Gas >>> Coal

Where the > symbol indicates better than.

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Chapter 23

Nuclear is Only Choice

We are covered a lot of ground, but the data point to nuclear reactors as the direction to go. The biggest public objection to nuclear is the fear factor. We will address the public fear factor with Table 1 that gives the normalized death print of each energy source. *Let nuclear be promoted as safe, plentiful, no toxic or fossil fuel emissions, cheaper if mass reduced for small nuclear generators, no steam explosion risk, low sabotage vulnerability especially when buried 30 feet underground, waste problem reduction, and burning of nuclear waste.*

Table 1. Energy Death Prints.

Energy Source	Mortality	Rate (deaths/trillion kWhr)
Coal – global average	100,000	41% of global electricity
Coal – China	170,000	75% China's electricity
Coal – U.S.	10,000	32% U.S. electricity
Oil	36,000	33% 8% of U.S. electricity
Biofuel/Biomass	24,000	21% global energy
Natural Gas	4,000	22% global electricity
Solar (rooftop)	440	<1% global electricity
Wind	150	2% global electricity
Hydro – global average	1,400	16% global electricity
Hydro – U.S.	5	6% U.S. electricity
Nuclear – global average	90	11% global electricity
Nuclear – U.S.	0.1	19% U.S. electricity

Table 2 evaluates the ability of all fossil fuel free energy sources with their ability to dependably power large populations. Nuclear has by far the highest power density and capacity factor. Finally, nuclear is the only non-fossil fuel free source that can power large populations.

Table 2. Finally, evaluation of fossil fuel free energy sources.

	Power Density W / m^2	Capacity Factor %	Power all Large Populations
Uranium Nuclear	241	92%	**Yes**
Thorium Nuclear	(241)	(> 92%)	**Yes**
Wind	1.8	15% - 40%	No
Solar	6.6	10% – 25%	No
Hydroelectric	0.14	39%	(No)
Geothermal	8.2	74%	No
Biomass	0.08	55%	No

The last point is to address the ability to make a thorium or IFR reactors that lives up to its goals. The effort has an advantage in that the nuclear physicists and engineers in the 1940s delivered an atomic bomb in just 2-years and 9-months. They had only the laboratory nuclear experiments of the 1930s and scientific theory. The fusion, or hydrogen bomb, was conceived in 1941 by Edward Teller and Enrico Fermi with only their faith in physics, and when developed, it worked as envisioned. The nuclear physicists and engineers have a good track record, and there is much more data supporting the thorium reactor than was available for atomic bomb.

That Manhattan Project had the benefit of four coordinated Nuclear National Labs with large budgets – Los Alamos, Argonne, Oak Ridge, and Hanford. More national labs were added including Sandia, Savannah, Lawrence-Livermore, and Idaho National Labs to the nuclear effort. The power is there to solve difficult problems. Our public focus should not be on patching our baseload energy sources with intermittent, unpredictable, and incapable renewables. While solar and wind have a large popular following, their inability to solve the energy challenge for the world is apparent. Our energy and budgets should be focused on leading edge power generator research and development. The thorium molten salt reactor has a proof of concept and should be a major focus of United States reactor engineering.