Central Coast Climate Science Education
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Desert Tortoises, Birds, Nuclear Waste and Climate Change: Difficult Tradeoffs

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The majority of my friends are on the liberal side of the political spectrum. So, when we gather, nearly all of us agree that reducing greenhouse gas emissions by drastically reducing our use of fossil fuels is a very high priority. But the agreement stops there.

There are disagreements, often strong, over the tradeoffs between environmental issues and the need for *non-greenhouse gas producing sources* of *electrical* energy. (For which I will use the abbreviation NGPS) There are also strong disagreements concerning the relative merits of the three main sources of this NGPS energy: solar, wind, and nuclear. There are, of course, other NGPS of electrical energy like geothermal and hydropower, but the ability for these to grow to the extent required is relatively limited. Reducing, or eliminating, greenhouse gas emissions from other sectors, e.g. transportation, industrial and residential usage is a separate topic which I will not emphasize here.

This is no doubt the most contentious essay I have written and will likely please nobody. So be it, for the main message is this: **The over-riding consideration must be the reduction of carbon dioxide** and the other important but less dominant greenhouse gas emissions. It is thus past time, one the one hand, for those critics of any of these three energy sources to accept the fact that no mitigation of their environmental concerns is going to be 100 percent satisfactory. But on the other hand, it is also past time for the proponents of any one, or all, of these three energy sources, to dismiss out of hand the legitimate concerns of those holding these concerns as being the irrational positions of "environmental extremists."

From this point of view, I want to examine these three--solar, wind, and nuclear--in turn.

First, however, I want to correct (I hope once and for all) a common **fallacy** voiced in connection with all three of these energy sources: Namely, that the greenhouse gas emissions produced in the construction of solar panels, wind turbines or nuclear reactors cancels out the emissions saved during the lifetimes of their operation. ***This is totally***

incorrect for all three of these energy sources, especially when compared to the emissions produced during the typical lifetimes of fossil fuel sources of electrical energy, namely natural gas and coal.

Studies of this issue are called "life cycle" or "end-to-end" analyses and do what the name implies: estimate the total emissions associated with all aspects of that energy source, from construction, operation, (typically assuming 30-year lifetimes) and disposal. The latest, most comprehensive analysis I have been able to find, which attempts to summarize many previous such analyses, and adopts a consistent common set of assumptions, is given here.[1]

The results are given in units of "grams of carbon dioxide per kiloWatt-hour (kWh) of produced energy:

Here are the median results for coal, natural gas, solar (silicon), wind, and nuclear:

Coal	Natural gas	Solar	Wind	Nuclear
975	660/450	48	10	10

(The two values for natural gas are for straight combustion-powered turbines and combined-cycle[2] natural gas generating plants.)

While solar is higher in terms of the life cycle emissions for both wind and nuclear, it is 10 times superior to even combined-cycle gas generation and 20 times that of coal. ***The objection that any of these produce as much in the way of emissions all the way from construction to disposal, as they save during their lifetimes, is simply false.***

Let us now consider the issues involved in each of these three NGPS of energy.

SOLAR ENERGY

The two most frequently stated concerns regarding solar energy are:

1) Environmental damage at the sites of large (utility-scale) solar "farms"
2) Environmental damage from the mining of the materials used for the manufacture of the panels and that associated with manufacturing and disposing of, old panels.

An additional criticism is the large amount of acreage taken up by large utility-scale solar farms. But the largest such land use is in arid, desert areas which have limited utility otherwise provided that item (1) is adequately addressed.

Environmental damage at installation sites

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[1] https://www.nrel.gov/analysis/assets/images/nrel-jisea-nicholson-box-plot.jpg. A much older analysis for nuclear energy gave a substantially higher value; I believe the more recent one is more reliable.

[2] https://www.ge.com/gas-power/resources/education/combined-cycle-power-plants. These plants use the waste heat from the gas combustion-driven turbine is routed to drive a steam turbine and increases efficiency by about 50 percent.

I should first note that about 25 percent of the total U.S. solar energy power is from small (mostly rooftop) residential and commercial installations whose environmental impacts are negligible, so I will address only utility-scale installations. And, since California generates the largest percentage of this energy, I will concentrate on these California installations.[3]

There are currently well over a dozen utility-scale solar farms having a capacity of 250 MW or greater in California, nearly all in the desert areas of eastern Southern California. There are also similar ones in nearby Arizona and Nevada. In these desert areas, a significant concern is the endangered desert tortoise. In a recent effort to mitigate the harm that might be done to these animals in a large solar farm under construction near Pahrump, Nevada, biologists worked with the solar contractors to relocate the tortoises to an adjacent piece of desert and to build a fence around the solar farm area to keep them out. This was not entirely successful, as the stress of relocation and some hungry badgers killed about a third of them. It is thought that this loss was exacerbated by the severe drought, though since this initial loss, things seem to have stabilized.

Closer to home, the developers of the Topaz solar farm in the Carrizo Plain in eastern San Luis Obispo County worked with biologists and took mitigation of environmental impacts seriously. I can recall though, that there were protests against its construction with people holding up signs to "Stop the Rape of the Desert." However, according to a November 2017 report from the Sacramento Office of the U.S. Fish and Wildlife Service[4] *"California's Carrizo Plain is alive with a stunning diversity of rare and protected wildlife…The Carrizo Plain is also home to two new solar energy projects that are shining examples of how solar energy development can generate clean power and local jobs, while conserving and protecting threatened and endangered species.*

More recent updates[5] are available, and there did not appear to be negative impacts from the Topaz farm, however the effects of the drought had widespread impacts. Very recently, Jason Dart from Althouse and Meade Inc. kindly gave me this update for which I am very grateful:

"I can say that since construction was completed, we saw a significant increase in kit foxes using the solar farm. The vegetation management has done very well in promoting native bunchgrasses and we have a slowly increasing population of small mammals (prey base for kit fox). Unfortunately, the last couple years have seen increases in coyote in the area and that seems to have negatively affected the kit fox numbers. Not to mention taking a hit on our sheep. We are continuing to monitor kit fox numbers and distributions with tracking collars and plan to keep that going for the foreseeable future."

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[3] In 2020, California generated about 30,000 gigawatt-hours of solar electric energy and imported about 6000 more, mostly from Arizona. Nationwide peak capacity is 95GW and projected to reach 200GW in 2025.

[4] https://www.fws.gov/sacramento/outreach/featured_stories/2012/RenewableEnergy-CarrizoPlain/

[5] https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=146280&inline

These issues are typical of the kind of learning experience and tradeoffs that will have to be made between environmental concerns and the necessity to switch to NGPS of energy. There is a kind of "NIMBY" tendency to say something like "I am all for solar, but put it somewhere else." There are realities regarding the feasibility of such projects (e.g., location near existing transmission lines) which are involved in these tradeoffs.

Production and Recycling of used solar panels

As more and more solar energy comes online over the world, more and more essential minerals will be required, including silicon, indium, cadmium, and tellurium, and some of these are toxic. Thus, being able to recover some of the 'high value materials' could both reduce the environmental damage from their extraction and that occurring when the panels come to the end of their 25-30 year useful life and most be disposed of. Currently there is no Federal policy nor incentive for studying, much less implementing, a nationwide recycling policy, though there are a few States (including California) where this is being studied and legislation proposed. With this in mind the National Renewable Energy Laboratory (NREL) recommended a number of actions that should be taken to address this issue.[6]

There are already, however, some solar companies which have undertaken recycling on their own as well as some 'third party' recycling companies[7] but the costs for doing this are still rather high. And, of course, the problem is much larger world-wide compared to in the U.S. alone.

The conclusion I draw from this discussion is that we should vigorously pursue solar energy but that we must spend more thought and effort on mitigating these concerns. Or, as a mantra (attributed to former Energy Secretary Ernest Moniz) I will repeat when I discuss wind and nuclear energy:

*The fact that a problem **isn't** being adequately managed does not mean it **cannot** be adequately managed.*

Or, its equally important converse:

*The fact that a problem **can** be adequately managed does not mean it **is** being adequately managed.*

WIND ENERGY

The U.S. currently has about 120GW of installed wind generating capacity, a bit larger than the total solar capacity, with Texas having by far the largest, and much of the remainder in the Great Plains. As is the case for solar, there is the potential for a very significant increase in this capacity, both onshore and offshore. Thus, as in the case of

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[6] https://www.nrel.gov/docs/fy21osti/74124.pdf

[7] https://resource-recycling.com/recycling/2021/06/15/how-the-recycling-industry-is-preparing-to-tackle-solar-panels/

solar energy, it is important to consider the environmental impacts of both onshore and offshore utility-scale wind farms. As in the case of solar farms, I will address at the end of this section on wind energy the issue of disposal/recycling of the material, especially the vanes of the turbines.

I must repeat, however, what I said at the outset: *the emissions produced over the entire life cycle of wind energy farms is vastly smaller than the emissions produced by fossil fuel generation of the same amount of energy.*

I want to focus on off-shore wind, and specifically on the recently announced designation of a (now) 375 square mile area located from 20-40 miles off-shore from Morro Bay-Cambria, California.

Important note for residents of the California Central Coast: A webinar discussing this project, sponsored by the San Luis Obispo Tribune, took place on November 19th . It was recorded and I urge those of you who were not able to see it in real time to watch it here:[8]

I first will review some of the technical and energy aspects of this area.

Technical and energy aspects of the Morro Bay off-shore wind area

The following figure shows the proposed area for wind development

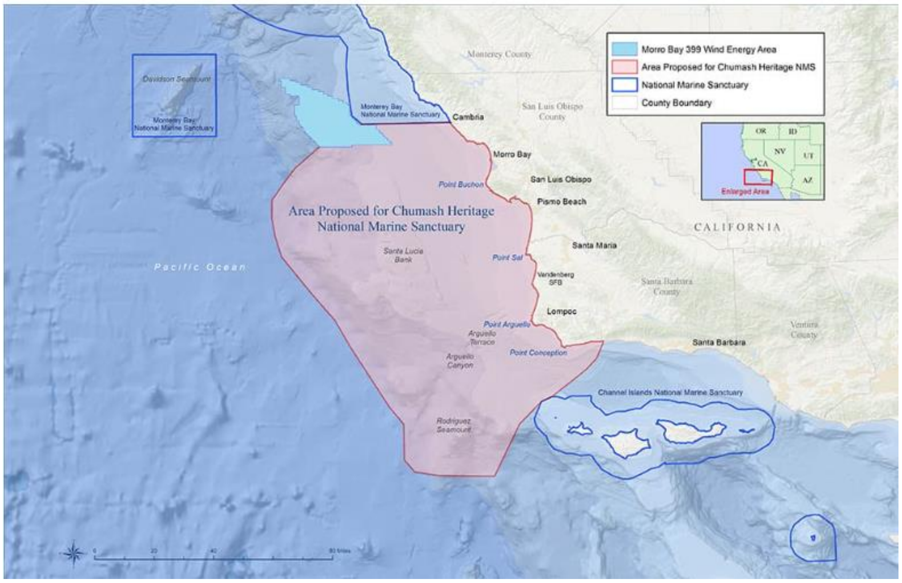

Figure 1) The proposed area (in light blue) for the Morro Bay offshore wind farm. The total area is (now) 375 square miles. The area directly above it outlined in blue is the Monterey Bay marine sanctuary while that in pink is the proposed Chumash Sanctuary. The wind farm varies from about 20 miles to 40 miles offshore—out to a depth of about 4000 feet, considered to be the limit for floating wind turbines.

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[8] https://www.sanluisobispo.com/news/local/environment/article254831132.html

A study carried out by Cal Poly Research Climate Scientist Dr. YiHui Wang and his collaborators analyzed the power output that can be expected from wind in this area, and importantly, its daily and seasonal variation. The following is a summary of the full report which is available in the link in this footnote.[9]

The largest offshore wind turbines considered, when running at full capacity, can generate 15MW. (A slightly smaller version was also considered, producing 12MW.) The total available power over the whole area is the same for the two cases, since the smaller turbines can be more closely spaced. The 15MW turbines are truly enormous: the blade lengths are about 400 feet long with the hub axis nearly 500 feet about the surface.

The power actually generated will of course vary markedly as the wind speed changes during the course of the day and with the seasons. The following graph taken from the Wang et al. paper shows the power generated vs. wind speed (in meters per second; 10 meters per second = 22 mph):

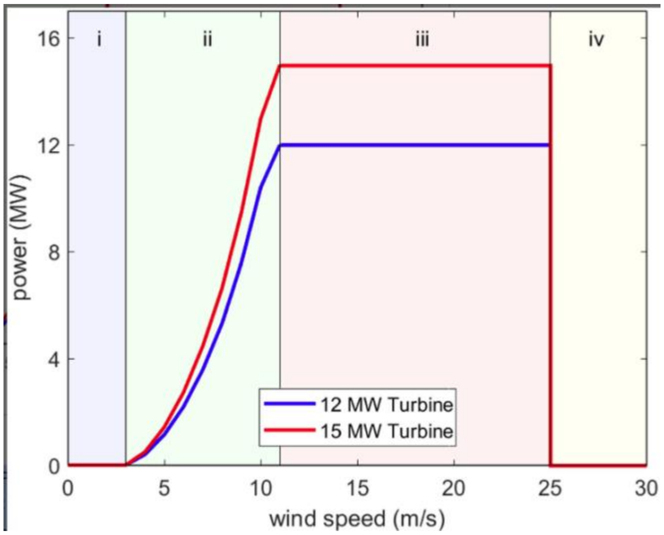

Figure 2. The actual power generated as a function of wind speed (meters/second) for the 12MW and 15MW turbines, as estimated by the National Renewable Energy Lab. In region (i) no power is generated. In region (ii) the power rapidly increases with wind speed and reaches full capacity throughout region (iii). In region (iv) the turbine must be shut down to prevent damage to the turbine.

The total energy that might be expected over the entire designated area is estimated by:

1)The number of turbines which are located in the area. If they are placed too close together, they will be in each other's "wind shadow". A minimum reasonable spacing is not definitively agreed to, but leads to an estimate of about 200-330 of the 15MW turbines over the designated area.

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[9] https://onlinelibrary.wiley.com/doi/10.1002/we.2646

2) Utilizing data on the fraction of time the wind is blowing at a certain speed, and hence the fraction of time a given amount of power is being generated, calculate the “capacity fraction”, the actual energy generated over the course of the year, compared to the energy if the full 15MW were always achieved. With the wind data set used by these authors, a capacity factor of about 0.5 resulted, though other data sets resulted in a higher capacity factor.

3) Finally, there will be some wind shadowing (“wake factors”) reducing this estimate as well as other losses, for example in the transmission of the power from wind turbine to the shore, which results in another reduction of about 0.8.

An interesting and important additional consideration is the daily and seasonal variation of this power. The following graph from the Wang paper shows some results:

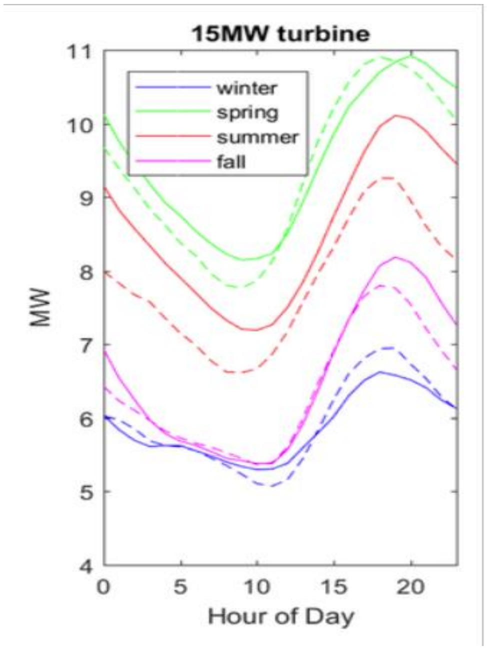


Figure 3: The variation in daily power generation from a typical 15MW turbine in the Morro Bay area for the four seasons shown.
(Ignore the dotted lines, which are for a different location.)

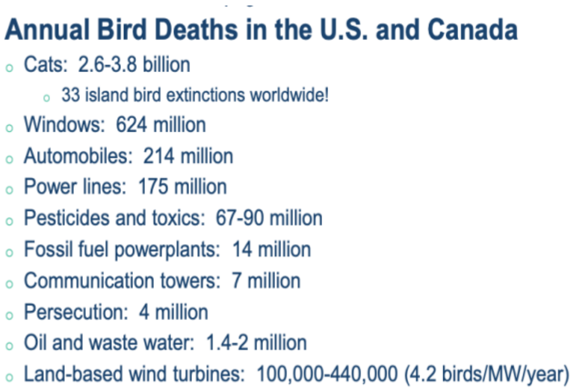
As Wang *et al.* note, the daily variation has the desirable property that the off-shore wind power ramps up in the late afternoon to early evening hours to help meet the typical “net demand.” The net demand is the power demand over and above that produced by solar and (currently) *land-based* wind. This steep increase in power must currently be met by expensive “peaker” power plants burning natural gas. This is especially important during the hot summer months when air conditioning is heavily used. The projected power during the winter season is quite a bit lower, but so is the demand for power.

The overall estimate of the annual power to be realized from full buildout of the Morro Bay wind farm is that the *average yearly energy output is between about 60% to 100% of the average yearly energy being produced by the Diablo Canyon Nuclear energy plant,* currently slated for shut down in 2025. And, as noted, it would help to reduce the need for more peaker power plants and the greenhouse gas emissions from these plants. It is therefore important to examine the environmental and economic impacts of such a facility.

Environmental Impacts of Wind with Special Emphasis on the Morro Bay Offshore Wind Development

As in the case of solar farms, the size of the total footprint required to produce a given amount of energy is large compared to that of nuclear energy. But, even for sites on farms in the Great Plains, except for the area in the immediate vicinity of the turbine, crops can be grown as well. In my judgement this concern is not an over-riding one.

Regarding the impact of wind turbines generally (onshore as well as offshore), bird loss is an issue. See here for a study prepared by the American Bird Conservancy.[10]
But it is also noted there that *climate change itself is a serious threat to bird species*, once again pointing to the inevitable tradeoffs that must be faced in dealing with climate change. It is also noted there that power lines kill a much larger number than turbines but do not also mention that cats kill perhaps two thousand times as many small species, as noted here,[11] (though the American Bird Conservancy says the actual number of bird deaths from turbines could be as high as 1,000,000 annually.)



Annual Bird Deaths in the U.S. and Canada

- Cats: 2.6-3.8 billion
  - 33 island bird extinctions worldwide!
- Windows: 624 million
- Automobiles: 214 million
- Power lines: 175 million
- Pesticides and toxics: 67-90 million
- Fossil fuel powerplants: 14 million
- Communication towers: 7 million
- Persecution: 4 million
- Oil and waste water: 1.4-2 million
- Land-based wind turbines: 100,000-440,000 (4.2 birds/MW/year)

This same point was made in a report by the National Wildlife Federation.[12]
(I am indebted to a representative of the Morro Bay Chapter of the Audubon Society for calling my attention to the NWF report. See also here[13] for the NWF's comments specifically regarding off-shore wind.)

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[10] https://abcbirds.org/blog21/wind-tUbine-mortality/

[11] https://www.boem.gov/sites/default/files/documents/West-Coast-Science-Exchange-20200108.pdf

[12] https://www.nwf.org/-/media/Documents/PDFs/NWF-Reports/2019/Responsible-Wind-Power-Wildlife.ashx

[13] http://offshorewind.nwf.org/

Although not specific to the Morro Bay development, a detailed discussion of the environmental impacts of off-shore wind farms has been carried out in Chapter 6 of a large study carried out by agencies of the European Union.[14]
Included in this study are several suggestions for mitigation measures that may reduce the impacts on birds and marine mammals. The NWF report cited above contains similar suggestions for mitigation of bird loss:

Among these suggestions:
*The farther offshore and the higher the turbines, the less damage is likely to be encountered.
*Larger (and therefore fewer) turbines, as widely spaced as possible, are better than smaller, more closely spaced ones.
*Intermittent, rather than steady, audible and visual signals to birds for avoidance are more effective than steady ones, especially when combined with sensors which detect approaching birds.
*Curtailment of power production and stowing the turbine blades to orientations presenting minimum danger to birds during sensitive seasonal and daily periods.

More study is needed regarding the efficacy of such suggestions specifically for the Morro Bay project but preliminary studies by marine wildlife specialists at Cal Poly suggest to me that they can be dealt with adequately.

With respect to the Morro Bay development, another significant concern is the economic impact on the fishing industry. There are ongoing discussions with the fishing industry representatives, and the same Cal Poly specialists are carrying out detailed studies on the impact the wind farm has on fishing. It should also be noted that with a few hundred huge turbines well offshore, both the installation and maintenance of these turbines would seem to offer additional or alternative employment to fishermen familiar with working well offshore. Those that want re-training for such work should receive it and should be given priority for such jobs.

A note concerning “aesthetics”: An additional objection often heard regarding offshore wind developments is that it will “spoil the view”. I do not mean to dismiss such comments but this concern needs to be seen in light of what the actual development would look like to a person on the coast with the nearest turbines 20 miles away and the furthest 40 miles distant: This issue was investigated via simulations of how the turbines would appear from four selected vantage points. See here to view a video of these simulations, but note that the *most distant* of these *simulations* is 20 miles, which is the *closest* for the current proposed area. In my opinion this objection has little merit. (Unfortunately, you will need to watch a 25 second ad first) :
https://www.sanluisobispo.com/news/local/article244230927.html

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[14] https://ec.europa.eu/environment/nature/natura2000/management/docs/wind_farms_en.pdf

Finally, the proposed huge Chumash Marine Sanctuary, which abuts the wind farm area, appears to be moving forward.[15] Neither oil drilling nor further wind farm development would be permitted, though fishing will be.

Recycling of wind turbine blades

Wind turbine blades are now made of fiber glass material, and as in the case of most solar panels up till now, they have thus far been piling up in landfills. Recently however, GE, a major producer of wind turbines, has started a program to grind them up and utilize the material in cement production, thereby also reducing the CO2 output in the cement production process. See here[16] for a discussion of this as well as recycling of other renewable energy material.

Nuclear Energy

Among the three NGPS of energy considered here, the role of nuclear energy in combating climate change is by far the most contentious. Emotions run very high on this topic on the part of many who strongly oppose any use of nuclear energy as well as on the part of some who think it must play an absolutely essential or even dominant role in dealing with climate change.

Here in San Luis Obispo County these feelings are exacerbated because of the decision by the Pacific Gas and Electric company, (PG&E) the investor-owned private utility company serving this County, to decommission the Diablo Canyon Nuclear Generating power plant by 2025, the last nuclear power plant in California. Some would have preferred that the plant was never built in the first place, others that the decision to close it in 2025 was a grievous error and are working to reverse it, or at the very least to extend its operation for several years beyond 2025.

The local issue of Diablo Canyon Nuclear Power Plant Decommissioning

This decision was primarily an economic one, though significant political pressure was also present. The following account, (slightly edited for brevity) was kindly provided to me by a person familiar with this aspect of the decision and provides some details:

A huge hurdle to Diablo's continued operation has been the impending expiration of the ocean cooling water discharge permit, which would mostly likely be impossible to extend for a long period of time due to state environmental regulations and the highly controversial politics involved. To continue operation, Diablo would have to rebuild its cooling water intake and discharge system to use land-based large banks of mechanical-draft or huge hyperbolic concrete cooling towers. And this would require the use of fresh water, which is not available.

In addition to the many years that it would take build the new system, the cost of building a land-based system was estimated to be several billion dollars, and would require approval from the

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[15] https://www.sanluisobispo.com/news/local/environment/article255668886.html

[16] https://blog.ucsusa.org/james-gignac/wind-turbine-blades-recycling/

Coastal Commission. Construction would not be financially feasible without major financial and regulatory support by the State.

Additionally, PG&E has little interest in taking on such major technical and financial burdens, especially during the turmoil of wildfire lawsuits and significant and very costly changes in technical power delivery systems such as under-grounding of many miles of power supply lines in mountainous terrain. In view of these considerations, PG&E wishes to leave the nuclear era behind.

Here are some additional comments on the capacity factor and economics of continued DCNP operation.[17]

"…There is no guarantee of "steady baseload power" from a 40-year-old nuclear power plant. Unit 2's failed main generator was replaced for nearly $100 million in 2019, but failed again in 2020, working only 30% of that year and narrowly squeaking by during the peak load energy crunches. The complex and costly repairs of aging systems are likely to multiply in the ensuing years….Diablo is too expensive, with $1.25 billion in annual above-market costs estimated by PG&E for 2020. Over a decade (minus inflation), that's $12.5 billion – or 62.5% of PG&E's proposal to underground distribution lines over the next 10 years."

However, impetus towards keeping DCNP open beyond 2025 was provided by a recent Stanford/MIT study which argued that the plant should be kept upon until 2035 or even 2045 and by a recent opinion piece by former Obama administration Energy Secretaries Chu and Moniz. Thus, while it is not certain that decommissioning will take place by 2025, it is important in any case to construct as much wind, solar and other NGPS of energy as soon as possible.

Some basic scientific and technical aspects of nuclear energy

Regardless of one's position on the role of nuclear energy, it is desirable to be acquainted with some of the basic scientific and technical aspects of nuclear energy.

Here is a very good resource[18] for basic information on the science and technology of nuclear energy, as well as the issues posed by it. The group was formed initially by several graduate students in nuclear engineering at the University of Michigan, who have maintained the organization since graduating.

A likely criticism of accepting information from this group is that they "have a vested interest" in nuclear energy. This is certainly true to the degree that they elected to get their training in this field, but it does not mean *ipso facto* that they cannot provide objective information any more than we should *ipso facto* discard what Anthony Fauci has to say about infectious diseases simply because he is employed to study infectious diseases. To those skeptical of this group's objectivity, the following statement of their "Philosophy" may provide at least some degree of assurance:

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[17] These are excerpts from more extended commentary by David Weisman, Legislative Director Alliance for Nuclear Responsibility. I have not independently verified the statements made.

[18] https://whatisnuclear.com/

In order for a technology to be convincingly superior to others, it must not only present compelling advantages, but also must concede to its weaknesses and demonstrate acceptable responses to its harshest criticism. Nuclear energy has drawbacks. We won't try to cover these up, but rather will try to present them clearly and explain or propose solutions to the problems. Too many times have we read that "this or that is the only thing that can save the planet." We will avoid this hysteria and strive to provide calm and true information and perspectives.

(In fact, I have heard advocates of nuclear energy make exactly that claim that nuclear energy is "the only thing that can save the planet.")

The following summary draws upon sources, mostly within the pages to be found in the website given in footnote 18 but also elsewhere. (There is a form on which readers are invited to submit questions or comments to them. Regrettably they have not responded to several attempts of mine to answer questions I sent them.)

The most common nuclear reactor in the U.S. (a "light water reactor") uses the very heavy element uranium, with *atomic number* 92. One of the isotopes[19] of uranium, ^{235}U , has the property that, when bombarded by neutrons, it "fissions"--splits into two other elements each having roughly half the atomic number of uranium—a bit like an amoeba dividing into two. In the process, a large of amount of energy is produced which generates heat, which in turn is used to power turbines to produce electricity.

The most common isotope of uranium is ^{238}U, which does not readily undergo fission. (But see below regarding 'fast' reactors.) Both are radioactive elements, but ^{238}U has a half-life[20] about as long as the age of the earth while ^{235}U has a half-life about 6 ½ times shorter, so when uranium is mined most of it is ^{238}U with only about 0.7% as ^{235}U**.** In order for the material to be viable in a light water reactor, the uranium must be "enriched" so that about 3-5% is in the form of ^{235}U.

These *fission products* and are highly radioactive. Crucially, during the fission process two or three additional neutrons are produced and some of these may in turn cause more atoms of ^{235}U to fission. Evidently this could cause a run-away chain reaction. To prevent this, material which strongly absorbs some of these neutrons is inserted to maintain a stable, constant energy-producing chain reaction. Material which slows ("moderates") the fast moving neutrons must also be employed in these reactors.

When most of the ^{235}U has been used up, the resultant highly radioactive and very hot "nuclear waste" is removed and stored in huge pools of water for a few years until some of the heat and radioactivity has dissipated, whereupon it is then moved to on-site

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[19] The *chemical* properties of every element are defined by its *atomic number*—the number of *protons* in the nucleus of that element, or equivalently, the number of outer electrons. But there are *isotopes* of that same element which differ in the number of *neutrons* in the nucleus and may have very different *nuclear* properties from one another. Uanium has atomic number 92, and the isotope ^{235}U has 235-92 = 143 neutrons. ^{238}U on the other hand, has 146 neutrons but has very different *nuclear* properties. As explained in the text, ^{235}U "fissions" when bombarded by slow-moving neutrons whereas ^{238}U does not.

[20] Radioactive elements decay "exponentially": For a half-life of 10 years, if you start with one ounce of that element, in 10 years you will have ½ ounce of it left. After 20 years you will have ¼ ounce left, and after 30 years 1/8 ounce etc.

reinforced concrete “dry casks”. The material in these dry casks consists mostly of the ^{238}U, most of which did not undergo nuclear reactions, and the fission products noted above. But also crucially, an isotope of the element plutonium, ^{239}Pu which plays a prominent role in discussions of the disposal of nuclear waste as well as in discussions of nuclear proliferation. The ^{239}Pu is produced when a neutron in the reactor interacts with a ^{238}U atom.

The amount of energy which can be produced in the relatively small amount of nuclear fuel present in reactors is truly amazing. In **Appendix 1** I have provided a striking example illustrating the *energy density* of this fuel compared to the energy density of gasoline.

Positive Aspects of Nuclear Energy

The most obvious positive benefit of nuclear energy is that it provides a fairly constant supply of NGPS of energy without the disadvantages of the intermittency to which wind and solar energy are subject. And, as noted at the outset, the life cycle, or end-to-end, production of a given amount of energy is, along with wind energy, very low.

Problems raised by nuclear energy

Two caveats and a general remark

- Some of the following issues may be significantly ameliorated by new reactor designs, which are discussed below.
- Most of the following discussion concerns nuclear energy *specifically in the United States*. The situation may be very different in other countries, also discussed below.
- Because of the contentious nature of this topic, one must be on guard against “confirmation bias” whereby one’s opinions lead to selective quoting of evidence. This is not easy to avoid and some subjectivity inevitably arises.

There are three main concerns raised by widespread use of nuclear reactors.

Nuclear weapons proliferation

Serious accidents at nuclear reactor sites

Disposal of radioactive waste

(An additional moderate concern is the large amount or ore that must be mined to produce nuclear fuel.[21])

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[21] Between 20,000-400,000 metric tonnes (one metric tonne equals= 1.1 U.S. ton) of ore is required to power a one-gigawatt nuclear plant for a year, depending upon the uranium content of the ore. See: https://css.umich.edu/factsheets/nuclear-energy-factsheet. This yields the roughly 3500 metric tons of ^{238}U which in turn is required to produce the 27.6 metric tonnes of enriched uranium. But this is still vastly smaller than the roughly 3.6 million tonnes of coal to produce the same amount of energy.

I believe that a significant amount of the strong feeling against use of nuclear energy reflects the horrific results of the dropping of two nuclear bombs by the U.S. on the Japanese cities of Hiroshima and Nagasaki. While I understand the arguments put forward for that action, I want to say unequivocally that I believe this was a tragic decision which I believe was wrong.

Nuclear weapons proliferation

There are two aspects to this concern:
First, while many of us would like to see complete nuclear disarmament, this is still a distant goal. And while I have heard it argued that as long as *some* nations possess them it is the "right" of *every* nation to possess them, it is hard to argue that the world becomes safer the more nations there are that possess nuclear weapons. Thus, one concern is that nations which have nuclear reactors, but do not possess nuclear weapons, may be tempted overtly or covertly to enrich uranium (or produce plutonium) to the point where nuclear weapons can be produced.[22] Iran is the obvious current case in point. As discussed in footnote 22, monitoring and inspection is carried out by the International Atomic Energy Agency but this is no guarantee that some nation states cannot circumvent it.

The second aspect of the proliferation issue is the possible role of terrorist groups, perhaps aided and abetted by corrupt or ideologically committed individuals, to enable construction, not necessarily of an actual nuclear weapon, but of enough dangerously radioactive material to construct and detonate a so-called "dirty bomb". As far the likelihood of a small terrorist group actually constructing a nuclear weapon, the obstacles are formidable as discussed here.[23] This is a fairly technical discussion but the last sentence is worth quoting: *"In summary, the main concern with respect to terrorists should be focused on those in a position to build, and bring with them, their own devices, as well as on those able to steal an operable weapon."*

In my opinion, the proliferation risk is very low *in the United States;* but in several other countries may be substantially higher.

While the circumstances and risks concerning the other two concerns, (on-site accidents and waste disposal) are different, they have in common the health effects of exposure to radioactive material. So before considering these two, here are some

Basics of health impacts of exposure to radioactive material

Note: *If you are not already familiar with the basic facts of radioactivity itself and the 3 different ways of measuring its presence and impacts, please see* **Appendix 2**. *In*

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[22] See the following incisive discussion which I have followed: https://whatisnuclear.com/non-proliferation.html

[23] https://www.nci.org/k-m/makeab.htm

particular, understand the difference between the actual level of radioactivity (measured in bequerels) and the concept of effective dose, measured in sieverts (or sometimes rem).

Radio-toxicologists make the distinction between "deterministic" exposure, which is exposure so severe that there is an unambiguous cause-and-effect relation between the amount of exposure and the damage to the body. And, for much lower doses, "stochastic" exposure—that is, it is only possible to estimate the *probability* that persons receiving a given 'effective dose' (measured in sieverts or rems) will suffer longer term impacts (like leukemia.) This is similar to the situation with, say, lung cancer and smoking: Not every smoker gets lung cancer and not every case of lung cancer involves a smoker. One can only assess the probability of increased cancer rates from a given amount of exposure.

There are two way of estimating the impact of such low level exposure: After a significant release of radiation has occurred, one can examine the population that was exposed and see whether the disease rate was higher than in a similar population that was not exposed. The second method is to use an extrapolation method, starting from an exposure high enough for the probability of disease to be known (call this the reference level) and then extrapolating down to (usually much) lower effective dose levels. What that correct extrapolation should be is a matter of controversy. The most common method is called the "linear-no-threshold" method. This means that one assumes that the probability of developing the disease is directly proportional to the effective dose level from zero all the way up to the reference level. Under this assumption there is *no* "threshold" dosage level below which no damage will occur. Many radio-toxicologists dispute this method of extrapolation and some suggest there is evidence that very low doses actually are beneficial.

Serious accidents at nuclear reactor sites and the resulting health impacts

Disclaimer: I have no training as a physician or a radio-toxicologist and there is still strong disagreement among experts who have such training. Discussion of this particular topic is especially subject to confirmation bias.

There has been about 40 years of experience dating from 1979 (when roughly 25% of the current generating capacity from nuclear energy existed) to the present time. In this time there have been three well-known serious accidents:
Three Mile Island, Harrisburg, Pennsylvania: March 28, 1979
Chernobyl, Ukraine : April 26, 1986
Fukushima, Japan: March 11, 2011

Recently, another one has come to light which I believe has some important lessons to teach us: The partial meltdown of an experimental liquid sodium cooled nuclear reactor, at the *Santa Susana Field Lab* near Simi, California, on July 13th, 1959. I will first comment on the three well-known ones first.

Chernobyl: This was by far the most serious, in terms of health impacts. The explosion at one of the reactors tore open the building and released large amounts of highly radioactive material into the surroundings and into the atmosphere. The design of this reactor was seriously flawed, lacked a proper containment vessel and the operators were poorly trained. The proximate cause of the explosion was high pressure steam when a chain of violation of safety protocols led to nuclear reactions rapidly overheating the water used for removing heat from the reactor with resulting melting of crucial components.

The "deterministic" health impacts (see the discussion above) were that 30 people died. There was a sharp increase in thyroid cancers, amounting to about 4000, especially among children in the vicinity, but according to a WHO study[24] only 9 of these resulted in death. The long-term "stochastic" health impacts, and the number of deaths over a much larger area (Ukraine and Belarus especially) which have already occurred or may occur in the future is strongly disputed. I will return to the dispute about stochastic health effects after discussing the Santa Susana incident and the waste mismanagement there.

Fukushima The nuclear meltdown and release of radioactive material was triggered by the tsunami resulting from an enormous (magnitude 9.0) underwater earthquake, the 4th strongest ever recorded. Earthquake detection sensors shut down the nuclear reactions as intended. However, the flooding from the tsunami disabled both the main and backup water circulation cooling system and the heat generated from the products of the reaction caused melting of components, explosion and fire, and release of radioactive material with contamination of the plant and nearby surroundings.

As in the case of Chernobyl, the long term health effects are in dispute, though it is certainly less than for Chernobyl. One recent assessment by the United Nation Scientific Committee on the Effects of Atomic Radiation[25] concludes that *"no adverse health effects among Fukushima Prefecture residents have been documented that are directly attributable to radiation exposure from the FDNP accident."*

While that may be true, the trauma of dislocation and evacuation appears to have had significant health effects, with studies documenting *"a high death toll among the elderly, increases in chronic diseases, and a decline in general well-being.*[26] The adequacy of the decontamination program to allow return to some of these evacuated areas is also disputed[27].

What is beyond dispute is that the economic and social consequences have been very serious.

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[24] https://www.who.int/news/item/05-09-2005-chernobyl-the-true-scale-of-the-accident

[25] https://www.unscear.org/docs/publications/2020/UNSCEAR_2020_AnnexB_AdvanceCopy.pdf

[26] https://www.science.org/content/article/physician-has-studied-fukushima-disaster-decade-and-found-surprising-health-threat

[27] https://www.greenpeace.org/static/planet4-japan-stateless/2021/03/ff71ab0b-finalfukushima2011-2020_web.pdf

Three Mile Island The Three Mile Island nuclear accident involved a chain of failures of both equipment and operator response and training. The nuclear reactions themselves were halted automatically in the process, as at Fukushima, but failure of the cooling system again resulted in partial meltdown of the core, as the fission products continue to produce heat, and this in turn generated explosive hydrogen gas which resulted in release of some radiative material over the course of a couple of days.

Again, the health impacts of this accident are in dispute and quoting of different estimates offer examples of confirmation bias. In the following account[28] it is stated that *"comprehensive investigations and assessments by several well respected organizations, such as Columbia University and the University of Pittsburgh, have concluded that in spite of serious damage to the reactor, the actual release had negligible effects on the physical health of individuals or the environment.*

There was some evidence however, that neonatal thyroid issues and infant mortality was higher than expected in some areas around Three Mile Island following the accident[29], and in adult thyroid cancer according to a study published in 2013[30], where the author states that the "*Thyroid cancer incidence since the TMI accident was greater than expected in the counties analyzed when compared to local and national population growth. This supports a link to chronic low level radiation exposure and thyroid cancer development",* but adds the cautionary note that *"Despite these findings, a direct correlation to the accident remains uncertain as incidence rates may coincide with other factors, and original data were limited."*

Because of uncertainties and disagreements about the impacts of low level exposures, rather than debate the number of casualties, it seems clear that these three were all serious incidents. The one proximate cause they have in common is that water was used to remove the heat from the reactions. Even after nuclear reactions ceased, failure of the circulation system caused steam-driven explosions and/or melting of components.

Design and procedural improvements have certainly lessened the likelihood of similar incidents in the U.S. and in the 40-plus years since Three Mile Island there have been no further incidents in these water-cooled large reactors. It seems impossible to provide a reliable estimate of the probability of a further accident or the seriousness of it. At the end of this essay, I give my conclusion of the best path forward.

Santa Susana Field Lab

I am basing the following comments on the MSNBC Documentary "In the Dark of the Valley"; I have not independently verified this material except for a Wikipedia article.[31]

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[28] https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html - effects

[29] The full article is behind a paywall: See here for abstract: https://www.jstor.org/stable/4312623

[30] https://pubmed.ncbi.nlm.nih.gov/23371046/

[31] https://en.wikipedia.org/wiki/Santa_Susana_Field_Laboratory

There is no more vivid demonstration of the maxim *"The fact that a problem* ***can*** *be adequately managed does not mean it* ***is*** *being adequately managed"* than the history at the Santa Susana Field Lab, where research on nuclear reactors and rocket engines was carried out. On July 13, 1959 a partial meltdown and release of radioactive material from a small-scale experimental liquid-sodium cooled reactor occurred. The reactor had no containment vessel and the incident was not made public. In addition, only very inadequate procedures for disposal of radioactive waste and hazardous rocket fuel chemicals were in place well before and well after the incident. Consequently, residents in a wide area of the Simi Valley were exposed to runoff and wind-blown toxic substances.

Eventually, the incidence of cancers, especially among young children, became evident. The following image, taken from the Documentary, shows the location of many of these and their relation to the Field Lab:

Figure 4. An image of reported cases of cancer in the area of the Simi Valley surrounding the Santa Susana Field Lab. Taken from the Documentary "In the Dark of the Valley".

While this image is suggestive it doesn't by itself demonstrate that these events were statsitically significant. However, some of the childhood cancers were of very rare types. In particular, it was reported that among children age 5 and under in the U.S. and Canada the number of a particular rare form was about 250 out of a population of these ages of about 21 million, leading to a rate per child of $p = 1.2*10^{-5}$. It was also reported that in this area of the Simi Valley there were about N= 110,000 children in that age group but 8 such reported cancers. Since $1.2*10^{-5} * 110,000$ is 1.32 we would expect only 1 or 2 such cases, so it doesn't require a sophisticated statistical analysis to conclude that 8 cases is highly unusual. But for those interested, in **Appendix 3** I show how the calculation is done. The result is that there is less than a one in 10,000 chance that 8 (or 8 or more) such cases would have occurred by chance. (But this is sensitive to the quoted North American rate of $1.2*10^{-5}$. If the true incidence were double this, then the chance occurrence of this number of cases is still small, but much larger, about 6/1000.

Two main conclusions I draw from the Simi Valley incident are that:

- The health impacts of low dosage radiation on young children, is still not adequately understood. There is some supporting evidence for this from Three Mile Island
- There is ongoing concern about relationships being too close between monitoring and regulatory agencies and the industries they are entrusted with regulating. Similar concerns have been raised with respect to one of these companies (Boeing) and the FAA regarding the two disasters of the 737 MAX 8 aircraft.

Disposal of radioactive waste

Of the three concerns regarding nuclear power, this is probably the one of most concern in the United States. Before discussing this concern and how it might best be alleviated, I believe an argument that I often encounter is specious: *"All the nuclear waste produced so far by all the reactors in the United States could be placed in a stack just 30 feet high on a football field."* This makes no more sense than arguing that if a glass of water contains only two lead atoms for every billion water molecules in must be perfectly safe, whereas in fact it is not safe. Nuclear waste is dangerous and must be handled with great care.

The discussion from the WhatIsNuclear website section dealing with waste,[32] I find to be an objective and very informative discussion and rather than give a complete summary I urge all who are interested in this topic to read it. However, I reproduce here this important plot showing how the radioactive material decays with time:

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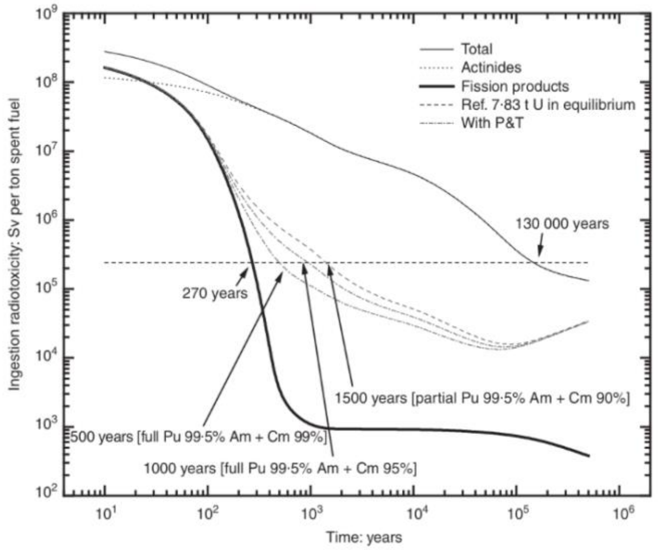
[32] https://whatisnuclear.com/waste.html



How dangerous nuclear waste is to eat as a function of time compared to eating natural uranium ore (dotted line). The various curves show that the toxicity decreases faster if you recycle the waste and burn the very long-lived radionuclides as fuel. (From Magil 2003)

Figure 5: The decay curve of "spent" fuel from a standard light water reactor. The figure and caption are from the reference in footnote 32.

The important point of this graph will be discussed further below in connection with the topic of 'reprocessing' and with the waste product associated with some 'fast neutron' reactor designs. Without these two possible technologies the very long decay time of ^{239}Pu renders the material highly radioactive for many tens of thousands of year, whereas most of the fission products themselves decay over a very much shorter time. The horizontal dashed line shows when the dosage (measured in Sieverts) has decreased to a level equivalent to that found in the amount of uranium ore necessary to produce the one ton of waste shown. This plot doesn't really tell us when the waste has decayed to a 'safe' level, since no one expects to eat a ton of waste or the equivalent amount of uranium ore! I have not found a reference discussing the actual amount of leakage that might result from long-term dry cask storage (see below) and resulting contamination of, for example, ground water, that might lead to measurable adverse health impacts.

<u>Dry cask storage:</u> Currently there is no U.S. central repository for nuclear waste and as far as I am aware, there is none being actively planned. Thus, after removal from a few years in pools, all the waste is currently being stored in steel cylinders surrounded by concrete ("dry casks.) So, an important question is what the useful lifetime of these dry cask storage containers is.

I have not been able to find any recent estimates or experimental data on the estimated lifetime of dry cask storage containers before some deterioration and leakage might be expected. The following is from a NY Times article in 2011[33]: *"Storage casks will be stored mostly in coastal or lakeside regions where a salt air environment exists," a*

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[33] https://green.blogs.nytimes.com/2011/08/09/researching-safer-nuclear-energy/

summary of the grant says. Cracking related to corrosion could occur in 30 years or less, and the Nuclear Regulatory Commission is studying whether the casks can be used for 100 years as some hope."

But a very recent update from the Nuclear Regulatory Commission states that[34]*:*
Since the first casks were loaded in 1986, dry storage has released no radiation that affected the public or contaminated the environment. There have been no known or suspected attempts to sabotage cask storage facilities. Tests on spent fuel and cask components after years in dry storage confirm that the systems are providing safe and secure storage." I have also been informed by a person close to the situation at the Diablo Canyon Nuclear Plant that new cask designs can reduce the required cooling time in pool storage to a year or so. Whether this also implies a much longer dry cask lifetime I do not know.

Regardless, eventually some nuclear power plants may run out of room for dry casks, and in any event, no one would argue that they can safely contain the extremely long-lived ^{239}Pu and other long-lived products until those have safely decayed. Thus, in view of the lack of a national repository in the offing, alternatives need to be considered.

An alternative long term waste storage proposal.

One such alternative, "boreholes," is described in footnote 32 and reference is made to a company, "Deep Isolation" which hopes to implement such a solution. You can find information about their technology on their website[35] , including this short video https://www.youtube.com/watch?v=bx786uMQ-1g as well as several "White Papers" and podcasts. The technique involves drilling very deep bore holes into stable geologic formations and inserting canisters containing the waste in these boreholes. A procedure for retrieving the canisters has been demonstrated should the need arise; alternatively, the boreholes can be permanently sealed. The drilling procedure is that developed by oil companies for 'horizontal drilling', but the company emphasizes that there is no high pressure fluid injected to fracture the rock, and 'fracking' is thus not involved, though the usual drilling fluid would be employed. An attractive feature of this approach is that such depositories can be placed in geologically suitable locations not far removed from a nuclear plant where the waste is produced.

Reprocessing of nuclear waste

Referring to the light solid curve at the top of figure 5, one sees that the waste has not decayed to the 'reference level' described above until 130,000 years have elapsed, due primarily to the very long life of ^{239}Pu. A technique called "reprocessing" (or sometimes "Partitioning and Transmutation") makes use of the 'spent' fuel in the normal nuclear reactor to achieve two objectives:

First, it chemically separates ("partitions") most of these long-lived isotopes from the fission products themselves. If this were done with 100% efficiency, then the remaining waste, consisting of only the fission products, decays in a vastly shorty time as indicated

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[34] https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/dry-cask-storage.html
[35] https://www.deepisolation.com/

by the heavy solid curve in figure 5, reaching the reference level in just 270 years instead of 130,000, making waste storage requirements far less daunting. The three dashed curves show the decay times when the separation efficiency is still very high, but not 100%.

Second, the spent fuel which has been separated from the fission products consists mostly of the non-fissionable ^{238}U. But this can now be 'transmuted' into ^{239}Pu by bombarding the ^{238}U with neutrons. This may seem a foolish thing to do, since we have just described how it is not desirable to have ^{239}Pu as a waste product. But the idea is that this transmuted ^{239}Pu can itself be used as nuclear fuel, thus avoiding mining a lot more ore and at the same time using up spent fuel. This is what is done in France. But the downside is that the process is complex and expensive and moreover there is concern that if the ^{239}Pu fell into the wrong hands before being inserted in the reactor it can be readily weaponized without the need 'enrichment'. For these reasons the U.S. has not utilized this technology.

Next Generation (Gen IV) and modular nuclear reactors.

A way around the downsides of reprocessing described above is best described in the context of a more general discussion of so-called "Next Generation" or "Gen IV" reactor designs and smaller-scale "Modular" reactors.

The idea behind the modular reactors is the "Henry Ford Model T" paradigm: Manufacture the components of the reactor in a central plant and ship them to the sites where these reactors are assembled and installed. They generally have substantially smaller electrical power outputs than the current 1 GW light water reactors and generally, but not necessarily, are not water cooled reactors.

"Gen IV" reactors refer to six classes of reactor designs considered by an international consortium of 14 countries to be the most promising for continued research and development. You can download and read about this consortium and the status of these 6 classes in their 2020 annual report.[36] I am providing this link simply to emphasize the international collaboration in this area and the very large amount of ongoing research. However, the details of these 6 classes, as described in this report, are highly technical.

I will briefly describe just three of these approaches, the companies developing them, and the significant advantages they offer over current designs in terms of safety and waste disposal.[37]

Sodium cooled "fast reactors"

(See for example: ARC ENERGY: https://www.arcenergy.co/technology)
Instead of water, liquid sodium is used. It has large heat capacity so that even if all power is lost to the pumps, the system will shut down and cool without any operator intervention and without any leakage of radioactive material. Such systems are called

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[36] https://www.gen-4.org/gif/jcms/c_178290/gif-2020-annual-report

[37] I am indebted to Mr. John Lindsey for passing on this information.

‘walk-away’ safe. (See the short demonstration video of this safety aspect in the link above.)

Another version of this basic approach is the ‘traveling wave’ reactor, (now more properly called a ‘standing wave’) reactor being developed by Terra Power.[38]
This company’s work has received a lot of publicity, no doubt owing in part to the involvement of Bill Gates.

The ‘fast’ in ‘fast reactors’ refers to the speed of the neutrons involved. Rather than slowing them down as current reactors must do when fuel enriched with ^{235}U is used, the fast neutrons interact with the plentiful ^{238}U, producing ^{239}Pu which is itself the fuel but which is consumed in the reactions. This design has significant advantages: It does not require a huge amount of uranium ore to be mined. Alternatively, it can also use the spent fuel from present reactors as its own fuel, thus consuming some of the waste already existing. Moreover, the waste product from these reactors is largely free from the long-lived ^{239}Pu and related isotopes, placing far less demands on the waste disposal problem, as described above. And finally, in the TerraPower design, a single fueling/waste removal cycle need be carried out only every 40 years rather than the current 18 months or so from current reactors. A downside of using liquid sodium is that it will burn in contact with air or water, so lots of attention must be devoted to preventing leakage of the liquid sodium.

Molten fuel reactors: See for example Kairos Power.[39]
Their design is an interesting one in that it combines two concepts: It utilizes a low-pressure reactor with fluoride molten salt as the coolant. In some molten fuel reactors, the nuclear fuel is dissolved directly in the coolant. In their case, they combine the molten salt coolant with the idea of ‘pebbles’. There are tennis-sized balls in which the fuel and waste products are encased in a high-temperature resistant ceramic shell. However, many details of their approach are not available from their website (presumably because much of it is proprietary.)

See also, for example, the Canadian company Moltex[40].
Many details of their approach are likewise not available from their website but it also uses molten salt of some kind. Their SSR-W model is also a fast neutron reactor, and near-atmospheric pressure reactor, also said to be walk-away safe, and also uses spent fuel from present generation reactors as input fuel.

Concluding remarks on Gen IV reactors

It is easy to get carried away with the promotional material many of these companies post on their websites. A glance through the Gen IV website in footnote 36 makes it clear that there are still some issues requiring more research. Most of these companies promise reactors to be ready by 2030, though experience suggests we should view that with some

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[38] https://www.terrapower.com/oU-work/traveling-wave-reactor-technology/
[39] https://kairospower.com/technology/
[40] https://www.moltexenergy.com/

skepticism. Nevertheless, the very significant advantage I believe they offer in safety and waste disposal, plus the smaller scale and modular opportunities (so huge amounts of capital do not have to be raised for very large scale installations) justify continued support for further research and development of these reactors.

As a final comment on Gen IV reactors, I want to respond to a criticism made of them: *"It will take too long."* This makes no more sense to me than saying that we should not plant trees because it will take several years before they really begin to sequester significant carbon. We want to be at net-zero by 2050 and we should have all options available to deploy depending on the needs and circumstances nationally and globally.

A global survey and global perspective on nuclear energy

Nearly all of this discussion has been devoted to emissions reductions and energy supply in the U.S. What is appropriate in the U.S. is not likely to be so in many other parts of the world.

China: This is one country where nuclear energy will certainly play a significant role is China, though there are differing accounts of just how significant.

A report from the International Energy Agency (IEA) presents a path towards zero emission in 2060.[41] It is in response to President Xi's announcement that China will *"aim to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060"* and "*to the Chinese government's invitation to the International Energy Agency to co- operate on long-term strategies by setting out pathways for reaching carbon neutrality in China's energy sector."* In this "Announced Pledges Scenario" (APS) the growth of nuclear energy is equivalent to four 1-gigawatt reactors every year over the next 40 years, resulting in about 160 such reactors. Even so, the anticipated growth in variable renewables (wind and solar) is even larger. Table 2.1 in the report shows nuclear energy contributing about 15% of total energy, while solar plus wind contribute 38%. Fossil fuels still contribute 26% so it isn't clear how the claimed net zero is achieved, though probably some "carbon capture and storage" is involved. In the electricity generation sector (their Figure 3.2), renewables contribute 80%, with 45% of this from solar and about 10% from nuclear. It is important to keep in mind, though that "Announced Pledges" as set forth in this pathway do not necessarily represent reality. Sadly, coal is currently being heavily used.

A recent report from Bloomberg News[42] quotes sources in China saying that 150 new reactors will be built over the next 15 years, with 46 under construction or planned. Even so, further in this report we read that "*wind and solar will become dominant in the nation's energy mix."* with *"nuclear power, a close third."* China also is exporting reactors to other nations, with Pakistan their biggest customer. It is not clear whether

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[41] https://www.iea.org/reports/an-energy-sector-roadmap-to-carbon-neutrality-in-china

[42] This article may require a subscription: Search "Bloomberg November 2, 2021 China Nuclear"

these are operated by Chinese technicians or Pakistanis. It is also not clear what plans Pakistan or China itself have for waste disposal.

India India currently ranks 3rd among all nations in greenhouse gas emissions and with a rapid growth in population, GDP, and urbanization, will play a crucial role in determining whether global emissions reduction goal are concerned. Prime Minister Modi's pledge in Glasgow was for India to achieve net zero emissions, but not until 2070. A report from the International Energy Agency[43] projects energy usage up through 2040. In the electricity sector the most realistic scenario (see STEPS, their Table 3.2) projects coal to comprise 34%, renewables 56% of which 31% is solar. Nuclear comprises only 6%.

Russia Russia currently has about 29 GW of nuclear power with plans to increase this to about 43 GW by 2030. They also export reactors to other countries. They are heavily involved in the "fast" nuclear technology described above, and some of the old plants are being retired.

Africa Africa, especially sub-Saharan Africa ("Africa South") is expected to have the highest rate of population growth in the world, adding over a billion people between now and 2050. The per-capita electricity consumption in Africa South is currently only 3.5% of that in the U.S., so demand is surely going to grow tremendously.

The country of South Africa has two reactors generating 5% of the country's electricity and plans to install 2.5GW of additional nuclear capacity in the next few years, possibly including smaller modular units. Nigeria, by far Africa's largest country by population (over 200 million) is negotiating with the Russians for up to 4 reactors over the next decade. Ethiopia, the 2nd largest, is embroiled in a civil war, and it is hard to be sanguine about safe management of nuclear facilities in this and other African nations with volatile political situations.

While there is a world-wide trend for increasing urbanization, over a billion people in Africa are still expected to be outside urban areas in 2050, and without access to transmission lines from large urban centers. Under such circumstances even modular nuclear reactors are too costly and impractical. Mini- and micro-grids served by small solar installations are most likely to help meet demand over the next several decades in these rural areas.

Other areas. In other areas of the world, especially in highly politically unstable regions like the Middle East, in which corruption is common and adequate safety and regulatory oversight is questionable, I personally would not feel comfortable with widespread deployment of large GW-scale reactors, though the Gen-IV reactors may pose fewer risks. The example of Iran also illustrates the concern over nuclear weapons development under the guise of developing nuclear energy.

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[43] https://www.iea.org/reports/india-energy-outlook-2021

PATHS TOWARD NET-ZERO EMISSIONS; DO WE "NEED" NUCLEAR ENERGY TO BE A COMPONENT OF NET-ZERO EMISSIONS PATHS?

Before beginning this discussion, a comment on an additional true, but not relevant, argument voiced by nuclear energy advocates: *"The health impacts, by any measure, are far worse from coal than they are from nuclear energy"*. This is certainly true, but this is a false choice. I suspect most, if not all, of the readers of this post agree that we want to eliminate the use of coal as an energy source as quickly as possible. But the question is not coal *or* nuclear, it is rather the "best" mix of wind, solar, nuclear and other NGPS of energy to get us to net-zero CO2 emissions as quickly as possible and certainly by 2050.

I put "need" in quotation marks because it is a maddeningly imprecise word in this context. What we "need" to meet such a goal depends on a number of factors, including:

- The degree of reliability of our electricity supply (e.g. will we accept brownouts 1 %, 0.1% or 0.01% of the time?
- How much are we willing to pay?
- What degree of risk or environmental damage are we willing to accept?
- How will the price of all these sources of energy, together with energy storage technologies, evolve in the future?
- Will there be supply chain issues or will alternatives be found for critical materials?

Absent any way of giving definitive answers to any, let alone all, of these questions, I have instead used the following analysis of a set of sample 'scenarios' leading to net-zero CO_2 emission by 2050. It was produced by a consortium of energy experts in the SF Bay area, having, as far as I can tell, no axe to grind as far as a favorite energy source.[44] (And there have been many other proposed paths by other organizations.)

This publication examines several scenarios and here are a few excerpts from the Abstract:
"…We created multiple pathways to net zero …CO_2 emissions by 2050… They met all forecast U.S. energy needs at a net cost of 0.2–1.2% of GDP in 2050…Pathways with constraints on…land use…and technology choices (e.g., no nuclear) met the target but at higher cost… Least-cost pathways were based on >80% wind and solar electricity plus thermal generation for reliability. A 100% renewable primary energy system was feasible but had higher cost and land use."

A huge shift to electrification is supposed, and here are some excerpts in section 6.1 where this is described: (VRE stands for 'variable renewable energy', i.e. wind and solar.)

Our analysis shows that electricity from VRE is the least-cost form, not only of power generation but of primary energy economy wide, even when that requires investment in

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[44] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000284

complementary technologies and new operational strategies to maintain reliability. All cost-minimizing pathways to deep decarbonization are organized around using VRE to the maximum feasible extent, to supply both traditional loads and new loads such as EVs, heat pumps, and hydrogen production. As a result, electricity demand increases dramatically, to roughly three times the current level by 2050 (230% to 360% across cases;…This demand is met primarily by VRE in all cases. In the [least cost case], the generation mix was 90% wind and solar It is possible that dramatic cost breakthroughs in new generating technologies such as …Gen IV nuclear could result in a reduced VRE share, but the breakthroughs would need to happen soon in order to deploy them at the pace and scale required in these scenarios.”

The following figure shows the evolution of the sources of electricity generation from 2020 to 2050 in the least cost scenario.

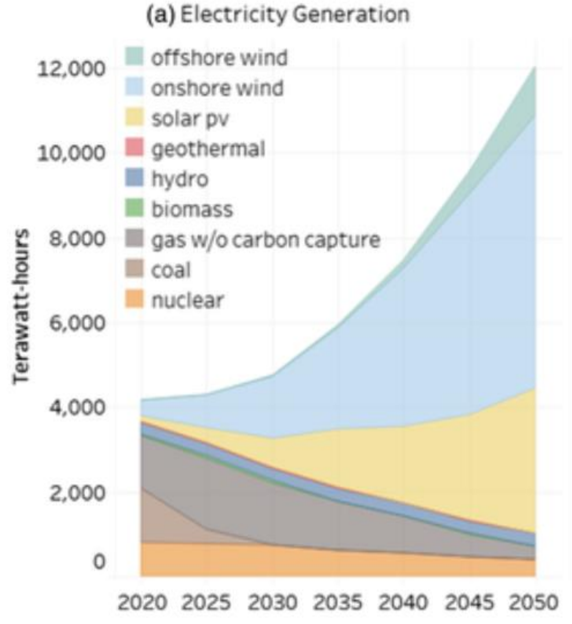

Figure 6. This is taken from section 6.1 of the pathway analysis referenced in footnote 44. Note that the actual amount of nuclear energy stays nearly constant though it declines slightly as some plants are retired. However, its percentage declines significantly since most of the new electricity comes from wind and solar.

This figure does not show the growth in stored energy capacity, but the authors conclude that a modest amount of gas generation capacity must be retained to assure adequate reliability. The CO_2 generated is offset by some sequestration.

In the scenarios with nearly 100 % reliance on wind and solar, in order to provide reliability during times of low wind and solar, the authors state that “*the resource that pairs best with a high VRE system is one with very low capital cost, because its role is to* *provide reliability for a limited number of hours per year. In this analysis, reliable capacity came mostly from thermal generation using gas without carbon capture The much higher initial capital cost of …nuclear plants as currently forecast could not be justified for such low utilization rates, and at the same time, they were uncompetitive with VRE for the bulk of operating hours.*

The authors also conclude that *"Energy storage was not competitive in meeting sustained energy deficits because the large quantity of energy needed required a large investment in storage, while the infrequent occurrence of such events resulted in very low storage utilization. These results illustrate why proposals for rapid retirement of gas-fired capacity are ill advised."*

Comments on Energy Storage and Li-Ion recycling

I believe the conclusion regarding energy storage not being cost competitive is uncertain as it depends on how rapidly such costs drop. I note that the Vistra energy company recently announced their intention to build a huge 600mW battery storage facility in Morro Bay[45] while HydroStor announced plans to install 400mW of compressed air-driven storage capacity along the California central coast[46]. Admittedly, this is a very small amount of storage compared to what will be needed nation-wide. The requirements for storage and gas-generating capacity will also depend on the nation-wide integration of the electrical grid and improvements in the grid are part of the recently passed Infrastructure legislation.

As in the case of disposal of solar panels and wind turbine blades, disposal of Li-I batteries and recovery of essential material, like cobalt, is a growing challenge but there are also growing efforts to deal with that challenge.[47]

CONCLUDING REMARKS

I have tried in this very long post to provide factual information with the aim of meeting the urgent need to reduce use of fossil fuels as an energy source while at the same time addressing legitimate environmental concerns regarding solar, wind and nuclear energy.

Regarding the path forward in the United States between now and 2050, my opinion is that no new large water-cooled reactors should be built in the U.S. No adequate waste disposal system is yet in place, but more importantly, they are extremely expensive. While some argue that this need not be the case, the actual track record is one of huge budget overruns and delays.[48] Even in nuclear-friendly France the same thing has

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[45] https://www.morro-bay.ca.us/DocumentCenter/View/15093/Vistra---Morro-Bay---Battery-Project-Presentation-022021

[46] https://www.energy-storage.news/hydrostor-seeks-approval-for-3-2gwh-compressed-air-storage-facility-in-california/

[47] https://spectrum.ieee.org/lithiumion-battery-recycling-finally-takes-off-in-north-america-and-europe

[48] https://www.wsj.com/articles/vogtle-nuclear-plant-in-georgia-faces-more-construction-delays-11623172361

occurred.[49] On the other hand, existing reactors should be kept operational until there are compelling economic or safety reasons for closing them. It will be very difficult, even with them operating, to meet reduction goals in the short term. Regardless, a way of safely storing existing and future waste must be developed, and the borehole technology seems to me promising.

Improvements in the electrical grid connectivity are urgent as are reductions in the cost of lithium-ion grid scale storage along with other storage capacities. Likewise, continuing research and development of Gen IV reactor designs should continue. I believe they offer very significant advantages in terms of safety and waste management. There is a reasonable chance they could be ready for use by 2030, but even if this is not the case the goal of net zero by 2050 is still a long way off. At present I think we simply do not know if, when, and where their use is going to be preferable to wind, solar and other renewables. Those decisions will need to be made on a case-by-case basis.

Mitigation of environmental damage from large scale wind and solar farms must be taken seriously but reasonable tradeoffs must be made in view of the climate crisis the world faces.

I acknowledge the many individuals who have sent me information on this topic but the views expressed are strictly my own, as are any and all errors. As always, I welcome reader input provided it is thoughtful, factual, and civil.

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[49] https://www.thelocal.fr/20191028/french-nuclear-power-plant-is-seven-years-late-and-costs-have-tripled/

APPENDIX 1: Illustrating the enormous energy density of nuclear fuel[50],[51]

I am always amazed at what a mere 8 gallons of gasoline will do for me in my modest Prius V: It will take me up steep hills and get me to the next gas station over 400 miles away. In this sense the "energy density" of gasoline is remarkable and it is what has made the internal combustion engine so popular. Regrettably, combustion of this fuel in such huge quantities is also one of the major contributors to global warming.

So, I have imagined the following situation to illustrate the astounding amount of nuclear energy that is contained in a small volume. Suppose that under the hood, instead of the Prius engine, there was a miniature nuclear reactor and that I drained the gas tank and instead filled the 8 gallon tank with the same nuclear fuel that goes in nuclear reactors. **Warning: don't try this at home!**

Assuming that the energy derived from consuming this fuel moves the car with the same energy efficiency that burning gasoline does, how far could the car go on one tank of this fuel?

An astounding 311 million miles, or 3 times the distance from the earth to the sun.

Here are the details of the calculation for any of you who wish to see them:
(I have used "scientific notation" and the symbol 10^4 means 10,000 etc.
So, 3.03*10^4 = 30,300 while 3.03*10^-4 = 3.03/10,000 or 0.000303)

1) Knowing the density of gasoline (0.803 grams/per cubic centimeter) and the volume in cubic centimeters of 8 gallons, (1 gallon =3785 cm^3) we calculate the number of grams of 8 gallons of gas : volume * density = mass of gasoline
8 * 3785= 3.03*10^4 cm^3*0.803 g/cm^3 = 2.43*10^4 g

2) Knowing how many ergs (a unit of energy) are released when one gram of gasoline is burnt, (4.8*10^11 ergs/g) we can calculate the total number of ergs released when all the 8 gallons are combusted. Of course, only a fraction of this goes into doing something useful, like driving up a hill or overcoming air resistance as we travel. *But we will assume below that this same fraction*

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[50] The calculation in this illustration is for *volume* energy density. The *mass* energy density is more relevant in some contexts, e.g. in electric vehicles. Scientists are working hard to increase the mass energy density of lithium batteries, since the lighter the vehicle the more efficient it will be. In the illustration in this appendix one gram of consumed nuclear fuel releases 2.74*10^16 ergs, while one gram of gas releases 4.8*10^11 ergs, so the mass density of the nuclear fuel is 57,000 times that of gasoline.

[51] I am much indebted to Steve Kliewer for checking these calculations and for helpful remarks clarifying these calculations.

applies to the nuclear calculation below. 2.43*10^4 g*4.8*10^11 ergs/g = 1.17*10^16 ergs of gasoline energy

3) Now consider the nuclear case;
Knowing the density of uranium dioxide (10.97) and using the same volume of the gas tank we calculate the number of grams of uranium dioxide.
10.97g/cm^3*3.03*10^4 = **3.32*10^5 g**
4) Knowing the weight of one molecule of uranium dioxide (mostly ^{238}U) we calculate the number of such molecules and hence the number of uranium atoms, (since each molecule of uranium dioxide contains one uranium atom) The ^{238}U atom contains 238 "nucleons"-- 92 protons and 146 neutrons, both of which weigh about the same, namely 1.67*10^-24 grams. So, one uranium atom weighs 238*1.67^-24 = 3.97*10^-22 g. Most of the oxygen is in the form of ^{16}O and since there are two of these, they together weigh 2*16*1.67^-24 = 5.34*10^-23g. Adding uranium and two oxygens together the molecule weighs 4.50*10^-22 grams.

5) The number of molecules, hence uranium atoms, in the tank is thus
3.32*10^5g/4.50*10^-22 grams per molecule = 7.38*10^26 uranium atoms

6) The fuel used contains 5 percent of ^{235}U and 95% ^{238}U, but only 80% percent of the ^{235}U can be consumed before the fuel would have to be replaced, so there will be 0.8*0.05*7.38*10^26 =2.95*10^25 ^{235}U atoms available for fission. (In a more exact calculation we would have taken into account the difference in weight between ^{235}U and ^{238}U but this makes hardly any difference.)

7) When a ^{235}U fissions it releases about 200 Mev of energy. (see: https://www.atomicarchive.com/science/fission/chain-reactions.html
An Mev = million electron-volts : a unit of energy, the energy acquired by an electron accelerated over a voltage of one Mev. (But 9 of this is in the form of neutrinos which we ignore since it requires about one light-year's thickness of lead to absorb their energy!) So we have about 191 Mev of useful energy.

8) To change from Mev to ergs we must multiply by 1.61*10^-6,
so, each time a ^{235}U fissions it will release 191*1.61*10^-6 = 3.08^10-4 ergs.

9) Since we have available 2.95^10^25 ^{235}U atoms, the total energy available to drive our car with a tank full of nuclear fuel is 3.08^10-4 ergs*2.95*10^25= 9.09*10^21ergs of nuclear energy

10) As noted above, we assume the same fraction of energy goes into driving the car from the nuclear reactor as did the energy from using our 8 gallons of gas to go 400 miles. We can thus set up the following proportion:

$\text{Miles}_{\text{nuclear}}$ /$\text{Energy}_{\text{nuclear}}$ = $\text{Miles}_{\text{gas}}$/$\text{Energy}_{\text{gas}}$

and solving this for $\text{Miles}_{\text{nuclear}}$

gives $\text{Miles}_{\text{nuclear}}$ = $\text{Energy}_{\text{nuclear}}$* $\text{Miles}_{\text{gas}}$/$\text{Energy}_{\text{gas}}$

Putting in the numbers (step 2 and step 9):

$\text{Miles}_{\text{nuclear}}$ = 9.09*10^21ergs *400 miles/1.17*10^16 ergs = **311,000,000** miles, **about 3 times the earth-sun distance!**

Appendix 2 What is radioactivity, the different measures of it, and health impacts of exposure to it.

What is radioactivity and what are the three kinds of radioactivity?

Among all the many isotopes of all the chemical elements, some are stable: the number of protons and neutrons for such isotopes remains constant forever. But for others, of which ^{238}U is an example, this is not the case. In the nucleus of ^{238}U as in many other isotopes, both stable and radioactive, there are, in a sense, strong "subunits", consisting of two protons and two neutrons. (The nucleus of the stable isotope of helium, ^{4}He is itself such a unit.)

Alpha decay: When ^{238}U decays it does so by emitting one of these subunits, called an *alpha particle* which has a positive electrical charge of +2. Thus, the resulting nucleus has two *fewer* protons, so its atomic number is 92-2 = 90 and this is the element thorium, and the resulting particular isotope is 238 – 2 protons – 2 neutrons = 234, so it is ^{234}Th.

Beta decay: But ^{234}Th is itself radioactive, but its mode of radioactivity is different. In essence, one of the neutrons in its nucleus is converted into a proton and an electron, but the *negatively charged electron* is spit out. This is called *beta decay*. The resulting nucleus thus has one more proton and thus atomic number 91, and is the element protactinium. But the sum of neutrons and protons has not changed so the isotope is ^{234}Pa.

Gamma decay. This series of radioactivity decays does not end there. In fact, radioactivity proceeds from one radioactive element to another until finally the stable isotope of lead is reached: ^{206}Pb. Along the way both alpha decays and beta decays occur. However, just as electrons orbiting the nucleus of an atom can be in high energy configurations, so the neutrons and protons in the nucleus itself can be in high energy configurations. During some steps following one of these alpha or beta decays, the resultant nucleus may initially find itself in such a high energy state. In such a case, rather than emit a positively or negatively charged particle, a gamma ray is emitted. Gamma rays carry no electrical charge, and is the same phenomenon as a "particle" ("photon") of visible light but carrying vastly more energy. Usually, the half-life for gamma ray decay is vastly shorter than for alpha or beta decay.

In summary, there are three kinds of radioactive decay modes: Alpha, Beta, and Gamma. They all interact with ordinary matter (including air and the human body) and will remove electrons from their parent atoms (i.e. ionize them), so these modes are a type of *ionizing radiation*, but so are x-rays from an x-ray machine. (Detection of the ionized air when exposed to radiation is how a Geiger counter works.)

These three types of radioactivity decay *differ strongly from each other in their ability to penetrate matter:*[52]
Alpha particles have little penetrating power, and cannot penetrate skin, so pose no harm unless emitted from radioactive material deposited within the body by breathing or ingestion. Some beta particles can penetrate a half inch or so of the body. Gamma particles are highly penetrating and requires several inches of lead before they are absorbed.

Because of these differences there are three distinct measures describing the level of radioactivity[53]: Each has its own units:

- The actual number of radioactive decays (no matter from which of the three types) occurring every second. The unit in use today is the "bequerel", abbreviated Bq. By definition, a sample of material that undergoes any one of these decays in one second has a Bq of 1. The relation between one gram of a given radioactive isotope is directly related to the weight of that isotope, hence the number of atoms of that isotope, and the half-life of that isotope: The shorter the half-life, the more rapidly the radioactive decays occur. One gram of ^{238}U has a Bq of about 12,350, while one gram of ^{226}Ra (radium) has a Bq of about 37 billion Bq, mostly reflecting the difference in half-life between ^{238}U (4.5 billion years) and ^{226}Ra (1,600 years)—but of course 1 gram of ^{238}U is easy to come by, one gram of ^{226}Ra is not.

- Absorbed dose: The amount of energy which is deposited from the absorption of radiation in a given weight of material. (The units are "grays" and "rads" and the precise definition is that one gray = 100 rads means that 1 Joule (a unit of energy) has been deposited in one kilogram of material. This will depend on the type of radioactive decay and the type of material doing the absorbing.

- Effective dose: This is the most relevant to the actual health impacts of radioactivity since it is an actual measure of the biological damage resulting in, for example, leukemia. The definition is necessarily less precise than for a bequerel since the health impact of various types of radiation (and this includes x-rays as well a radioactive decay) are not that well understood, especially at very low levels. The unit of measurement is a sievert (or millisievert.) Roughly speaking if a large group of people received a dose of one sievert it is usually assumed that the cancer rate among this group would be about 5 percent higher than a similar large population that did not[54].

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[52] https://www.cdc.gov/training/products/RN/page4976.html; this is an excellent elementary tutorial for the material described in this Appendix.

[53] https://www.epa.gov/radiation/radiation-terms-and-units This is a simple and excellent summary from the EPA.

[54] https://www.imagewisely.org/Imaging-Modalities/Computed-Tomography/How-to-Understand-and-Communicate-Radiation-Risk

Different organs in the body are more sensitive than others (e.g. reproductive organs and bone marrow. Also, dosage can be delivered by other sources, for example by a dental x-ray or a CT scan, not only from radioactivity. A CT scan of the chest delivers about 7 millisieverts, roughly equivalent to 2 years dosage from normal everyday background sources. A cross country airplane flight delivers about 4 *micro*sieverts

Appendix 3: **The statistics of the occurrence of rare childhood cancers in the Simi Valley**

The problem is analogous to rolling a die N times and asking what is the probability that it will turns out to be a "one" exactly k times, where 0 <= k <= N. If the die is "true" then the probability of rolling a "one" on any given try, p, is p = 1/6. The probability law follows what is known as the binomial probability distribution law, and the exact expression is:

$$\text{Prob}(k; N, p) = \frac{N!*p^{k}(1-p)^{(N-k)}}{k!*(N-k)!}$$

where k! is "k factorial" etc.

Here is the table giving the results for this simple case of N=8 rolls of the die

Number of ones	Probability	Cumulative Probability
0	0.232567981	0.232567981
1	0.372108787	0.604676783
2	0.260476172	0.865152955
3	0.104190469	0.969343424
4	2.60476209E-02	0.995391071
5	4.16761963E-03	0.999558687
6	4.16762021E-04	0.999975443
7	2.38149732E-05	0.999999285
8	5.95374331E-07	0.999999881

The sum of all the probabilities should be exactly 1.000000000 but because of rounding errors in the computer they do not quite add up to exactly 1.00000000

On the next page is the analysis for the Simi Valley case.

In the case of Simi Valley described in the text, $N = 110{,}000$ and $p = 1.2*10^{-5}$ and it is impractical to use the exact expression given above. However, for cases for which N is >>>1 and for which p <<<1 and when the observed number of observed cases (k) is not very large (8 in the Simi Valley situation) the following expression is an excellent approximation:

$$\text{Prob}\ (k;\ N,\ p) = [(N*p)^k * \exp(-N*p)]/\ k!$$

Here are the numerical results for this case:

Cases	probability	Cumulative Prob	Cum prob for k >=8
0	0.267135292	0.267135292	
1	0.352618605	0.619753897	
2	0.232728288	0.852482200	
3	0.102400452	0.954882622	
4	3.37921493E-02	0.988674760	
5	8.92112777E-03	0.997595906	
6	1.96264824E-03	0.999558568	
7	3.70099413E-04	0.999928653	
8	6.10664065E-05	0.999989748	6.10664065E-05
9	8.95640642E-06	0.999998689	7.00228120E-05
10	1.18224568E-06	0.999999881	7.12050605E-05
11	1.41869478E-07	1.00000000	7.13469271E-05
12	1.56056448E-08	1.00000000	7.13625341E-05

As we expected, one observed case has the highest probability, with 2 cases and no cases being the 2nd and 3rd most likely. ***The probability of having 8 cases is extremely unlikely, being less than 1 in 10,000.*** In situation such as these one generally calculates the probability of observing "k or greater" number of cases but the result differs only slightly from the case of k = 8 exactly. Note that the cumulatively probability in this calculation converges rapidly towards 1.0000000 as required.