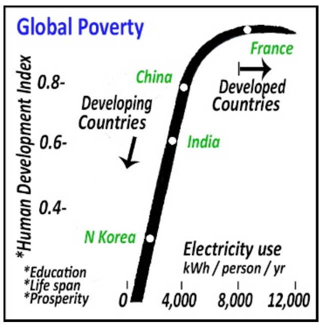
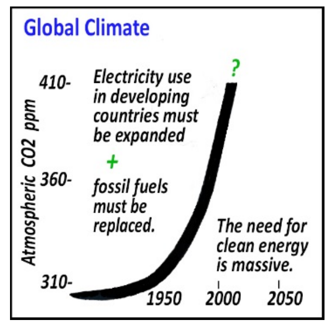
Why I Changed My Mind

Ron Gester, retired geologist & physician August 2021

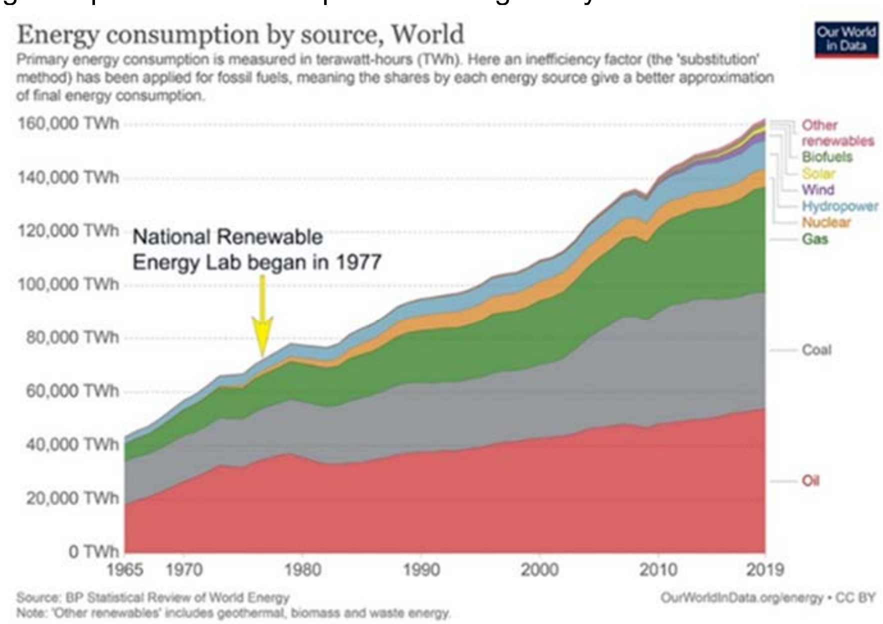
In the 1970s, I marched in opposition to nuclear power plants. In 2008, I began to realize that I knew a lot about nuclear energy … that just wasn't true. When I discovered how wrong I had been, I became obsessed with the quality of my information. I wanted to promote options for fighting climate change and global poverty that were supported by rigorous science and math. David MacKay's book, *Sustainable Energy – Without the Hot Air*, showed how. [1] After much effort, I concluded that nuclear energy was one of those options – perhaps the most important one – since clean energy is essential for fighting both climate change and global poverty. I realized that while other forms of clean energy were important, they would not be sufficient. What follows is a summary of why I changed my mind.





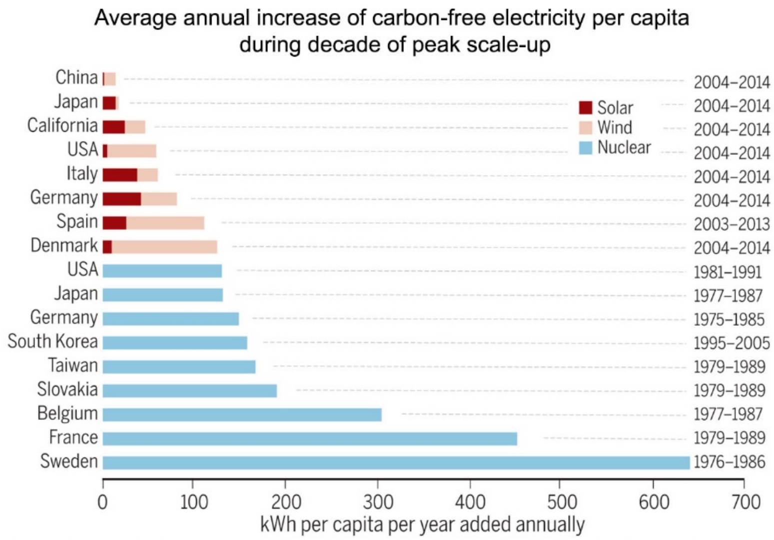
Moral obligation. I believe that I have a moral obligation to try to enhance the quality of life around the world. This belief led me to examine the United Nations' Sustainable Development Goals where I learned about their Human Development Index. This index has been used to track the connection between electricity use and human development for decades. [1,2] Cheap energy was essential to the progress of today's developed nations and developing countries deserve no less. However, the cheapest sources, fossil fuels, have imperiled the future of life on Earth. Therefore, if I hoped to promote development in poorer countries without using fossil fuels <u>and</u> simultaneously maintain prosperity in developed countries while replacing fossil fuels, I needed to identify safe and affordable methods of generating truly massive amounts of clean energy. [3]

Global perspective. Studying climate change caused me to question one of my long-held tenets: "If everyone just did a little, we could solve xyz." In the fight against climate change, it implies that actions like buying a fuel-efficient car, adopting a vegan diet, or installing residential solar panels are a path to success. Unfortunately, I concluded that they were not. As noted by David MacKay, "If everyone does a little, we'll achieve only a little." This was evident in our lack of success during the preceding 32 years of government promotion of conservation, efficiency, and renewable energy. [1] While these personal actions might help reduce local air pollution or signal my concern and commitment to others, they were detrimental if I believed they would make a difference in mitigating global warming or absolve me of my need to do more. Frequent news headlines claiming the rapid growth of renewable energy obscured reality. I realized that graphs, such as this one, were essential to keeping the problem in perspective. [2] When I began my study in 2009, solar and wind provided less than 1% of global energy consumption and fossil fuel use was growing. (In 2019, they



provided 3.3% and fossil fuel use was still growing.) I concluded that I needed to promote a source of clean energy that could scale up rapidly.

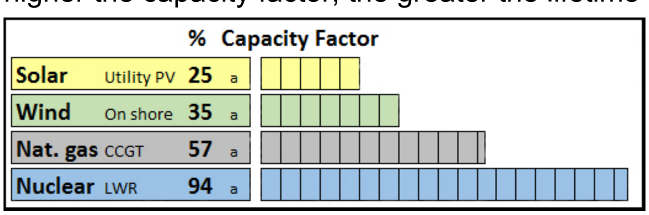
Global-scale response. I learned that France had rapidly expanded its nuclear energy generating capacity in response to the 1973 oil crisis. It built 56 reactors over the following 15 years. They currently provide 70% of the country's electricity. As data about the deployment of clean energy systems in other countries gradually emerged, it became apparent that nuclear energy has a solid history of scaling up more quickly than other clean energy sources. This graph displays the quantity of electricity per capita added annually during each country's fastest 10 years of solar, wind, and nuclear construction. [1] Although the results seemed surprising, they were readily explained by some well-established, but broadly under-appreciated, advantages of nuclear energy discussed below. New reactor designs using assembly line construction will probably further accelerate their deployment.



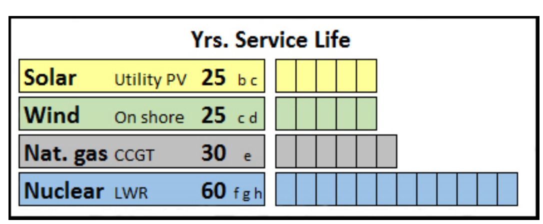
From "China-U.S. cooperation to advance nuclear power." J. Cao, A. Cohen, J. Hansen, R. Lester, P. Peterson, H. Xu. *Science*, 05 Aug 2016: Vol. 353, Issue 6299, pp. 547-548. Reprinted with permission from AAAS.

Advantages of nuclear energy. One of the concerns I had about nuclear power plants was that they were reportedly more expensive than other clean energy systems. I discovered that many of the comparisons were not "apples to apples" evaluations. The categories of cost varied and the basis for comparison was often incomplete. I learned that fair analysis required an equivalent accounting of each energy system's total life-cycle costs (e.g. construction, operation, maintenance, fuel, and decommissioning) and comparing them based on the total quantity of energy (e.g. per kWh) produced. This revealed three significant advantages of nuclear energy that I had not previously appreciated: capacity factor, service life, and fuel energy density. They provided important insights into each system's attributes and were my key to understanding the debate about costs.

Capacity factor is the ratio of a power plant's actual electrical energy output to its maximum possible electrical energy output over a period of time. It is generally expressed as a percentage. The higher the capacity factor, the greater the lifetime generation of electricity. This, of course, lowers the total cost per kWh. This graph depicts the average capacity factor for each source in the US in 2019. [a] The capacity factor of nuclear power plants was 3.8 times greater than solar, and 2.7 times greater than wind. This was primarily due to the intermittent nature of sunshine and wind.



Service life, or lifetime, is the number of years of operation before the system needs to be retired. The longer the service life, the greater the lifetime generation of electricity and the lower the cost per kWh. In 2018, the service life of nuclear power plants was 2.4 times greater than solar and wind, and 2 times greater than natural gas. [b-h] More recently, four nuclear reactors have received



license extensions to 80 years. In addition to reducing cost per kWh, such long-term durability is a key to scaling up rapidly, since less time and resources are consumed by replacing retired systems.

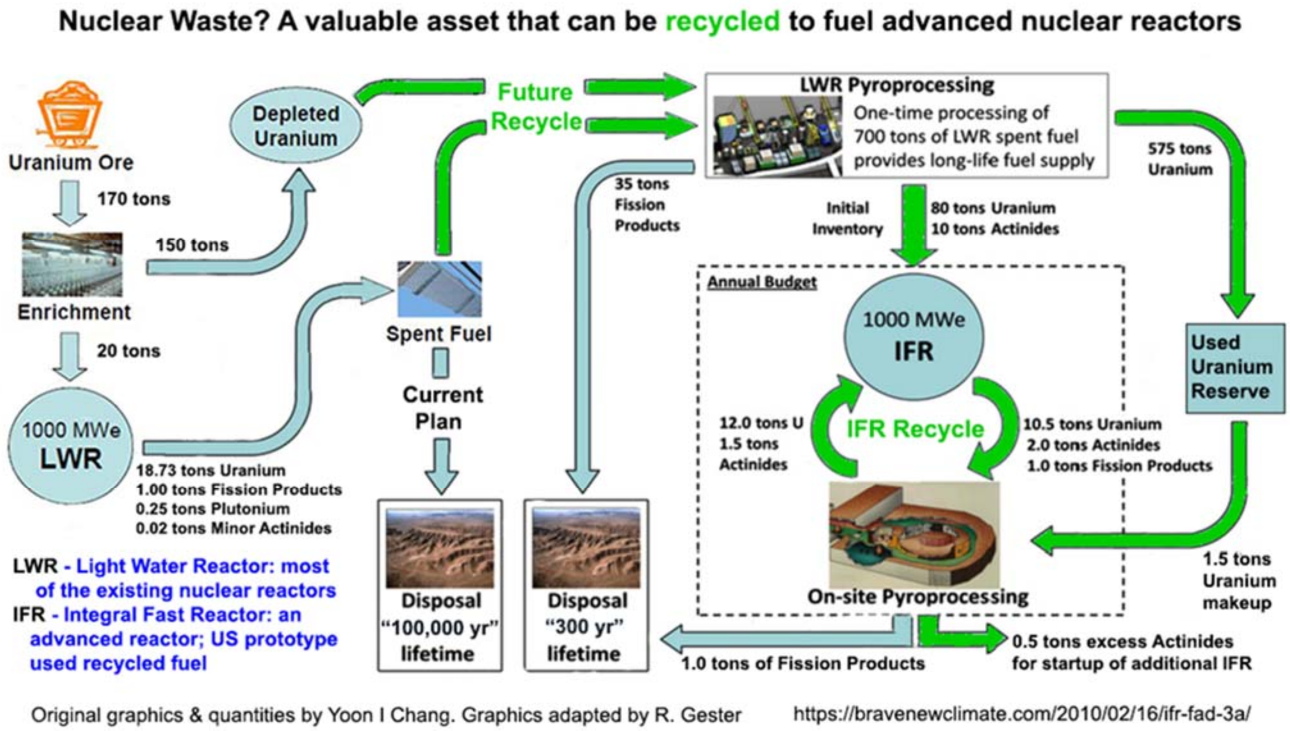
Energy density is the amount of energy stored in a unit of volume or mass. (Technically, the latter, energy per mass, is called *specific energy*, but it is common to ignore this distinction in general discussions.) The energy density of uranium … blew my socks off. [1-5] It was a significant and inherent advantage over all other current energy sources. By packing a large amount of energy in a small volume or mass, uranium fuel: 1) decreased the power plant's **resource use**, 2) decreased the volume of **waste**, and 3) increased the power plant's **reliability** compared to less dense energy sources. I was amazed by the scale of this advantage. In our current Light Water Reactors, for example, 1 kg of natural uranium will yield ~9,000 times more energy than 1 kg of natural gas in a gas-fired power plant. As impressive as that was, the <u>total</u> energy content of uranium is actually far greater than current reactors can utilize. Future reactors (e.g. Integral Fast Reactor) may yield closer to 77,000,000 MJ/kg. This was mind-boggling. A penny-size piece of uranium (0.36 cc) in such a reactor would provide more than 5 years of electricity for an average American home (10,649 kWh/y). [6,7]

Energy Source	Content in Joules		ref
Solar	1.5	µ J / m³	5
Wind @10mph	7	J / m³	5
Wood	18	MJ / kg	1
Coal	30	MJ / kg	1
Oil	42	MJ / kg	1
Gasoline	46	MJ / kg	1
Natural gas	54	MJ / kg	1
Uranium nat. LWR	500,000	MJ / kg	3
Uranium nat. IFR*	77,000,000	MJ / kg	4
*calculated; 1 MJ = 1,000,000 J; 1J = 1,000,000 µ J			

Resource use. I have been a nature-loving outdoor enthusiast since childhood. In the early days, we cooked our camp meals over fires from sticks found nearby. It was natural. It was, however, not sustainable. We eventually realized that we had to use gas stoves and other technology to lighten our impact. Climate change brought a similar message. The best way to protect nature was to find ways to reduce our use of its resources. So, I was alarmed by the spread of wind turbines and solar panels. Ridgelines and seascapes were becoming industrialized, fields were being fenced off to protect panels, trees were being cut down because they cast shadows … and the transition was just in its infancy. Solar and wind energy may be natural, but I realized they would not lighten our impact. When compared per effective megawatt (MW), nuclear power plant construction and operation use less concrete, steel, and land than solar or wind systems. [1-3] In fact, the resource use of solar and wind were actually greater than shown in this table. This was because solar and wind systems are intermittent, and therefore required another energy source as "backup" … for when there was insufficient sun (75% of the time) or wind (65% of the time). That other energy source was increasingly natural gas, also known as methane. In other words, whenever there was not enough dispatchable clean energy (e.g. nuclear, geothermal, or hydro) for "backup," solar and wind systems resulted in the added costs, resource use, and significant greenhouse gas emissions of gas-fired power plants. They were not as natural or green as I had imagined.

Resource use		Capacity Factor %	Service Life Yrs	Concrete t/MW-yr	Steel t/MW-yr	Land *3 ac/MW	Ref #
Solar	Utility PV	25	25	10.7	12.0	44	*1
Wind	On shore	35	25	52.0	13.5	71	*1
Nat. gas	CCGT	57	30	4.7	2.6	12	*2
Nuclear	LWR	94	60	7.5	0.8	13	*2
tons/MW-yr are short tons per megawatt adjusted by capacity factor and total years of expected service ac/MW are acres of land per megawatt adjusted by capacity factor							

Nuclear waste. Like many people, I was worried about nuclear waste. Therefore, I was pleased to learn that nuclear power was required to both contain all of its waste, and prefund the costs of waste storage and power plant decommissioning. That is worth pondering for a moment. If this had been required of all energy systems, especially those using fossil fuel, their true costs would probably have prevented our current climate crisis. As for nuclear waste storage, there are political and public debates about where that happens, but we know how to do it safely. [1-3] One of the more exciting prospects involves recycling the waste as depicted in the diagram below. [4] It utilizes a process called pyroprocessing that was developed at Argonne National Laboratory beginning in 1964. Four metric tons of used fuel were recycled during the program. Used in conjunction with an advanced reactor (e.g. IFR), this can 1) increase the energy yield of uranium by a factor of 150, 2) reduce the quantity of waste by ~95%, 3) reduce the complexity of waste storage requirements, and 4) eliminate the need for uranium mining for hundreds of years. [4-6] ANL is currently "working to improve the technologies' commercial viability by increasing their process efficiency and scalability." [7] I concluded that nuclear "waste" was, in fact, a massive energy resource that will probably benefit future generations.



Solar and wind waste. To gain perspective on the problem of nuclear waste, I examined the difficulties facing solar and wind energy. With smaller capacity factors, shorter service life, and profoundly lower energy density, their primary issue was enormous volume. For example, to match the electricity generated during the service life of a typical 1,000 MW nuclear reactor would require ~30 million, 17 square foot, 300-watt solar panels or ~11.5 thousand 120-foot long wind turbine blades. [1] Furthermore, to be able to provide electricity when there was no sun or wind, these systems would require "backup" energy systems. Whether this was mega batteries that have yet to be invented or gas-fired power plants, the waste from these would also need to be managed. Although there has been some effort to recycle solar and wind wastes, it has not been required or included in the cost of deployment. [2,3] I believe that this problem is solvable, and not an argument against using solar and wind. It is an argument for promoting even-handed discussions of waste management for all energy systems. Given the massive scale of global energy demand, it is going to be challenging.

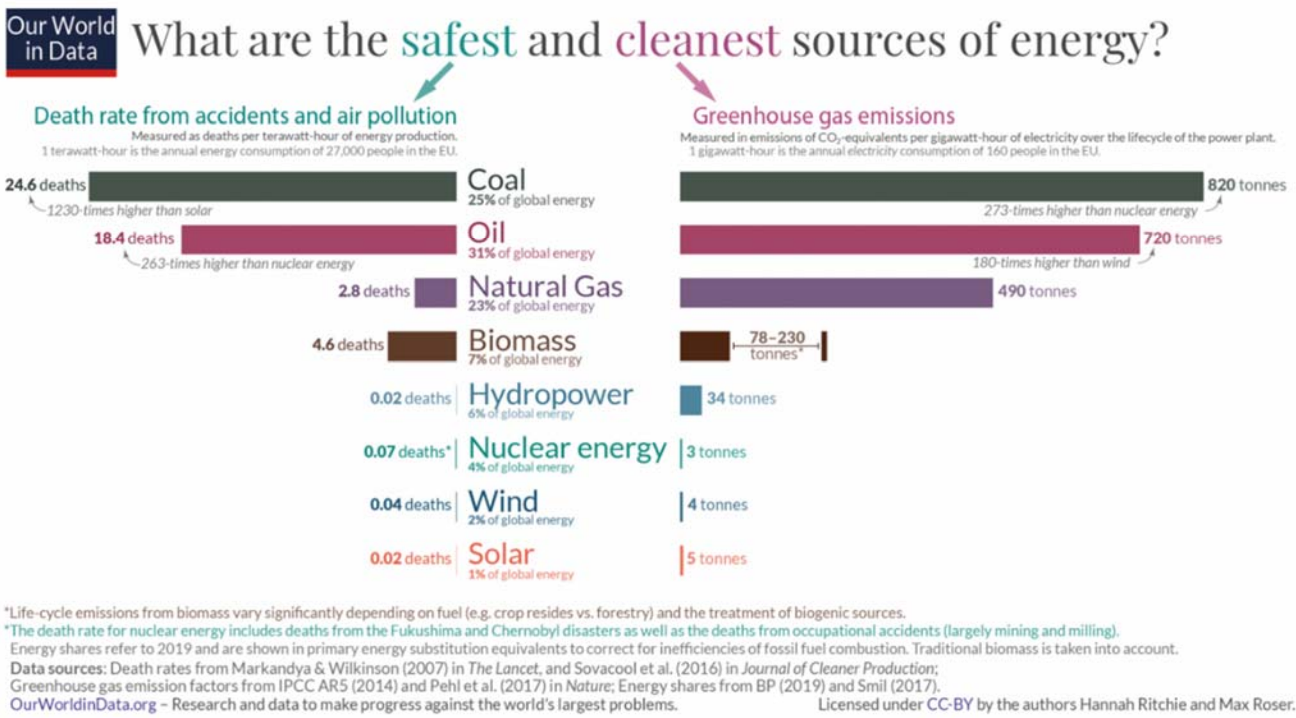
11,500 wind turbine blades?

It is difficult to put such numbers in perspective. The amazing photographs linked here depict just 870 blades (cut into thirds) being buried in a Wyoming landfill. It is a troubling perspective, but it deserves our attention.

https://www.bloomberg.com/news/features/2020-02-05/wind-turbine-blades-can-t-be-recycled-so-they-re-piling-up-in-landfills

https://www.gettyimages.com/detail/news-photo/pieces-of-wind-turbine-blades-are-buried-in-the-casper-news-photo/1222855019

Health risks. As a retired physician, I was particularly interested in the health impacts of our various energy options. I focused especially on the biological effects of ionizing radiation and the emerging science of cellular DNA repair mechanisms. I read extensively about Chernobyl, and corresponded with molecular pathologists researching the cancers linked to that event. I learned that ionizing radiation was a relatively weak carcinogen [1,2] and my heightened fear of it was the result of fiction, marketing, and cold-war propaganda. [3] Nuclear energy ranked among the safest (per TWh) and cleanest (per GWh) forms of energy. [4] This was partly because of the three advantages enumerated above, partly because of regulatory requirements, and partly because life has evolved mechanisms for managing damage from radiation and other harmful agents in nature (e.g. smoke, sunshine, oxygen). [5] The 0.07 deaths per TWh of nuclear energy in this graph includes a 2005 estimate of up to 4,000 future cancer fatalities due to Chernobyl radiation. So far, the data suggests there have not been any. [1,2] Graph is here: https://ourworldindata.org/safest-sources-of-energy



Reliability. For most of my life, I took electricity for granted. Power outages were rare events. However, during the past decade, that has changed. I learned that the fundamental problem was that grid reliability had become less of a priority. This is partly because most of the organizations that oversee the grid (e.g. Federal Energy Regulatory Commission, Regional Transmission Organizations, and the Independent System Operator) do not have sufficient authority. [1] Their primary tools for managing energy producers are market incentives – a web of ever-changing rules that have recently emphasized expansion of intermittent energy sources. As a result, the grid has become more vulnerable to the demands of extreme weather events. [2] Since these were likely to become more frequent with climate change, it was clear to me that reliability needed to be prioritized, and that nuclear energy was the best option. Why nuclear? In part, because nuclear power plants are extremely durable and compact, and in part because the energy density of uranium reduces the risk of fuel supply disruption. For example, as noted above, natural uranium yields ~9,000 times more energy than natural gas. In addition, the energy in uranium is released more slowly in the power plant than the energy in natural gas. Consequently, nuclear reactors can run for 18 to 24 months on one load of fuel. By comparison, gas-fired plants require a

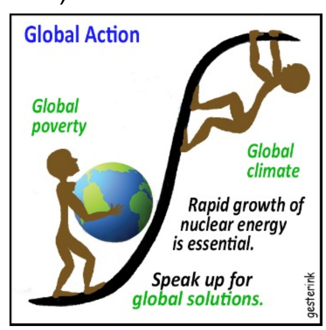

Texas largely relies on natural gas for power. It wasn't ready for the extreme cold.
The Dallas Morning News 2-17-2021

58 people died in last week's frigid weather. Some of them were just trying to stay warm.
The Washington Post 2-21-2021

continuous, just-in-time supply through pipelines that stretch for thousands of miles. A single load of uranium, therefore, provides the energy equivalent of hundreds of miles of gas pipeline and avoids the risks of pipeline failure due to construction accidents, sabotage, or extreme weather.

The cost of nuclear energy. Although fundamentally driven by concern for humanity and our environment, many of the reasons why I changed my mind were supported by the data showing the cost advantages of nuclear energy. This was, however, inconsistent with news headlines claiming that nuclear energy was too expensive. Part of the explanation lay in the "apples to apples" accounting described above. When costs were limited to fundamentals (e.g. construction, operation, maintenance, fuel, and decommissioning) that were normalized to a common denominator (e.g. kWh), nuclear energy was the least expensive. [1] When costs were not limited to these fundamentals, the result generally ceased to be an "apples to apples" comparison. For example, solar and wind energy costs have been reduced by subsidies and incentives for being clean. Nuclear power plants provide a variety of such attributes to the grid and grid operators, but they have not been subsidized. These include electricity that is not only clean, but also predictable, controllable, and reliable. In addition, nuclear power plants provide reactive power (vars) that helps maintain the voltage and support the grid. In view of the durable, long-term solutions that are needed to mitigate climate change, I concluded that nuclear energy was not too expensive. It was undervalued.

It's about time. As a retired geologist, I inevitably found myself thinking about time. I felt like I was witnessing a critically important moment in Earth history. Our species had made many mistakes, but we had learned so much. From the microscopic to the astronomic, we had unraveled so many mysteries of the universe and improved the lives of billions of people. [1] Now, we have discovered perhaps our gravest mistake. Our use of fossil fuels to advance human development has changed Earth's atmosphere and oceans. We have learned that unless we respond to this rapidly, the quality of life on Earth will suffer for millennia. [2] However, we know what to do and have been clearly called to action. [3,4] Unfortunately, instead of declaring a national emergency, our leaders responded with non-binding clean energy "goals" and inadequate measures, such as fuel efficiency standards and subsidies for intermittent energy sources. [5] Despite all the cleverness of our species, we have a difficult time evaluating and responding to threats that are invisible (e.g. radiation) or incremental (e.g. climate change). It is hard work. [6] It took time, but ultimately I concluded that the risks from nuclear power were small, whereas the climate risks that it could help mitigate were enormous and urgent. Nuclear power has recently gained additional public support [7], but if we hope to avoid major ecological and humanitarian tragedies, I believe that more people need to understand and promote its advantages. It's about time.



In conclusion, I changed my mind for a variety of reasons – the most important of which are summarized above. I have referenced sources for further details, so that I could keep my story short. The latter was tough, given the copious details that I have accumulated over the past 13 years. I have 10 binders and 112 computer folders with notes from books, articles, conferences, and an ongoing Google Group of climatologists and engineers. I have met hundreds of wonderful people who shared my concerns about climate and poverty. Many of them had also once opposed nuclear energy. It has been exciting to be part of this movement. It is a reason for optimism in an often-discouraging fight. The causes of climate change and global poverty are complex and deeply entrenched. My efforts to mitigate them feel small. *However, I have concluded that my best options are to 1) oppose the premature closure of nuclear power plants, 2) donate to the growing number of organizations that are promoting nuclear energy, 3) support politicians who promote an aggressive, war-like response to climate change, 4) find ways to give the next generation reasons to hope, and 5) share what I have learned with friends.* Useful links and references are attached. If you would like further information, please let me know. rgester@thesciencecouncil.com Thank you for your time.

Mothers for Nuclear An environmental organization started by two mothers, Heather Matteson and Kristin Zaitz, who work at Diablo Canyon Nuclear Power Plant. Their mission is to encourage pro-nuclear mothers to speak out and begin an international dialogue about nuclear power and environmental protection. https://www.mothersfornuclear.org/

Generation Atomic GA's mission is to energize and empower today's generations to advocate for a nuclear future. They are particularly active in trying to prevent the premature closure of nuclear power plants. https://www.generationatomic.org

Green Nuclear Deal A nationwide advocacy effort to articulate a new vision for nuclear growth as a way to create dignified high-wage jobs and re-establish ourselves as the global leaders of this critical technology. https://gndcampaign.org/

The Breakthrough Institute is a global research center that identifies and promotes technological solutions to environmental and human development challenges. https://thebreakthrough.org/

Decouple podcast Dr. Chris Keefer, ED Physician, Toronto, Canada. "There are technologies that decouple human well-being from their ecological impacts. There are politics that enable these technologies. Join me as I interview world experts to uncover hope in this time of planetary crisis**."** https://anchor.fm/chris15401 or Apple or Spotify

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Why I changed my mind
[1] MacKay, D. (2009). *Sustainable Energy – Without the Hot Air.* UIT Cambridge Ltd. Web. Print. 371 pages. Quote page 3. Free online here: http://www.withouthotair.com/ or 10 page synopsis here: http://www.withouthotair.com/synopsis10.pdf

Moral obligation
[1] "Electricity Consumption and Development Indicators" (2016). Center for Global Development. Web. https://www.cgdev.org/media/electricity-consumption-and-development-indicators
[2] "Human Development Index (HDI)" (2020). United Nations Development Programme. Data Center. Human Development Index. http://hdr.undp.org/en/content/human-development-index-hdi
[3] Rosling, H. (2010). TED video: "The Magic Washing Machine." Gapminder Organization. Web. https://www.gapminder.org/videos/hans-rosling-and-the-magic-washing-machine/ Resource of interactive global data. I also recommend video: "Population growth explained with IKEA boxes"

Global perspective
[1] National Renewable Energy Laboratory (NREL) began as the Solar Energy Research Institute, which opened in 1977. Designated a national laboratory of the U.S. Department of Energy in 1991 and name was changed to NREL.Web. https://en.wikipedia.org/wiki/National_Renewable_Energy_Laboratory
[2] "Energy consumption by source, World." 1965 – 2019. Published online at OurWorldInData https://ourworldindata.org/grapher/energy-consumption-by-source-and-region?stackMode=absolute&country=~OWID_WRL using data from BP Statistical Review of World Energy 2020. Arrow to show year of NREL founding added by R. Gester

Global scale response
[1] Cao, J., Cohen, A., Hansen, J., Lester, R., Peterson, P., Xu, H. (2016). "China-U.S. cooperation to advance nuclear power." *Science,* Vol. 353, Issue 6299, pp. 547-548. Web. https://science.sciencemag.org/content/353/6299/547

Advantages of nuclear energy

Capacity factor

[a] Mueller, M. (2020). “What is Generation Capacity?” US Department of Energy. Office of Nuclear Energy. Web. https://www.energy.gov/ne/articles/what-generation-capacity

Service life

Why so many references? The “service life” of generation systems is gradually increasing for a variety of reasons. The values I used are conservative for each energy source. Each industry claims that the average service life of their systems is (or will soon be) greater than I have cited: 5 to 10 years more for solar and wind; 10 years for natural gas; and 20 years for nuclear. If I had used the higher numbers for each, the advantage of nuclear remains roughly the same.

[b] "New study finds increase in expected useful life and decrease in operating expenses over time for utility-scale PV.” (2020). Berkeley Lab. Web. https://emp.lbl.gov/news/new-study-finds-increase-expected-useful-life

[c] “Useful Life.” US Department of Energy. National Renewable Energy Lab, Energy Analysis. Web. https://www.nrel.gov/analysis/tech-footprint.html

[d] Carrara, S., et al., (2020). *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonized energy system*. European Commission, Web. https://eitrawmaterials.eu/wp-content/uploads/2020/04/rms_for_wind_and_solar_published_v2.pdf

[e] “Depreciation Analysis for Power Generation” (2016). Florida Public Service Commission, Power Generation Division. Web. http://www.floridapsc.com/library/filings/2016/07554-2016/Support/OPCs%201st-38-Attachment%203.pdf

[f] “What's the Lifespan for a Nuclear Reactor? Much Longer Than You Might Think” (2020). US Department of Energy. Office of Nuclear Energy. Web. https://www.energy.gov/ne/articles/whats-lifespan-nuclear-reactor-much-longer-you-might-think

[g] English, E., (2020). “Nuclear Power Plant Life Extensions Enable Clean Energy Transition” International Atomic Energy Agency. Web. https://www.iaea.org/newscenter/news/iaea-data-animation-nuclear-power-plant-life-extensions-enable-clean-energy-transition

[h] “Lifetime of nuclear reactors” (2021). Section 13, Nuclear Power Reactors. World Nuclear Organization. Web. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx

Energy density

[1] “Energy Density” (accessed 3-2021) Wikipedia. Web. https://en.wikipedia.org/wiki/Energy_density

[3] “Heat Values of Various Fuels.” World Nuclear Association. Web. https://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

[4] Calculation: each U-238 fission yields 190 MeV of useable energy:

A mole yields 6.023 E23 (Avogadro)*190 MeV*1.602 E-13 (joules/MeV) = 18.3 TJ

Uranium-nat. energy/kg = (18.3 TJ/238 g)*1000 g/kg = ~77 TJ/kg = ~77,000,000 MJ/kg

[5] Layton, B. (2008). “A Comparison of Energy Densities of Prevalent Energy Sources in Units of Joules Per Cubic Meter.” International Journal of Green Energy, 5: 438-455. Web. https://www.drexel.edu/~/media/Files/greatworks/pdf_sum10/WK8_Layton_EnergyDensities.ashx

[6] “How much electricity does an American home use?” (2020). US Department of Energy, Energy Information Agency. Web. https://www.eia.gov/tools/faqs/faq.php?id=97&t=3 In 2019, the average annual electricity consumption for a U.S. residential utility customer was 10,649 kWh. (This is roughly 3 times the amount used by European households such as Germany.)

[7] Calculation: 77,000,000 MJ/kg x 19.1 g/cc x 0.36 cc/penny = 529,452 MJ thermal

529,452 MJ thermal x 0.385 efficiency of conversion thermal to electrical = 203,839 MJ e

203,839 MJ electrical x 3.6 MJ/kWh = 56,622 kWh. 56,622 kWh /10,649 kWh/y = 5.3 years

Resource use
[1] Carrara, S., et al., (2020). *Raw materials demand for wind and solar PV technologies in the transition towards a decarbonized energy system*, European Commission, Web. https://eitrawmaterials.eu/wp-content/uploads/2020/04/rms_for_wind_and_solar_published_v2.pdf
[2] Kaplan, S. (2007). "Concrete and Steel Requirements for Power Plants" Congressional Research Service, Washington DC. skaplan@crs.loc.gov PDF. 7 pages
[3] Stevens, L. (2017). "The Footprint of Energy: Land Use of US Electricity Production" STRATA. Web. 25 pages https://www.strata.org/pdf/2017/footprints-full.pdf

Nuclear waste
[1] Gil, L. (2020). "Finland's Spent Fuel Repository" International Atomic Energy Association. Web. https://www.iaea.org/newscenter/news/finlands-spent-fuel-repository-a-game-changer-for-the-nuclear-industry-director-general-grossi-says Onkalo is a deep geological tunnel style repository.
[2] "Deep Isolation: Frequently Asked Questions" (2021). Deep Isolation, Inc., Website https://www.deepisolation.com/faqs/ Very deep, drill hole style repository.
[3] Adams, R. (2020). "Atomic Show #273, Interview: Liz Mueller, CEO of Deep Isolation." Rod Adams hosts a podcast series that discuss many energy-related topics, often from an atomic energy point of view. Web. https://atomicinsights.com/atomic-show-273-liz-muller-deep-isolation/
[4] Brook, B. (2010). "IFR FaD 3 – the LWR versus IFR fuel cycle." Brave New Climate. Web. https://bravenewclimate.com/2010/02/16/ifr-fad-3a/ (In addition to consolidating two flow diagrams into one (with permission of Yoon I. Chang), I have added quotation marks to the 300 and 100,000 years of disposal lifetime. These numbers reflect real and important differences in the materials being disposed, but they appear rather absolute and impervious to the high probability that future generations will have better ideas than just disposal. – RG)
[5] Till, C.E. & Chang, Y.I. (2011). *Plentiful Energy: The Story of the Integral Fast Reactor, the Complex History of a Simple Reactor Technology, with Emphasis on Its Scientific Basis for Non-specialists*. United States: CreateSpace. Print. 390 pages
[6] Hannum, W., Marsh, G. & Stanford, G. (2005) "Smarter Use of Nuclear Waste." *Scientific American*: 84-91. Web. http://www.nationalcenter.org/NuclearFastReactorsSA1205.pdf
[7] Williamson, Mark (2020). "Pyroprocessing Technologies: Recycling used nuclear fuel for a sustainable energy future." Argonne National Laboratory, US Department of Energy, Web. 12 pages https://www.ne.anl.gov/pdfs/12_Pyroprocessing_bro_5_12_v14[6].pdf

Solar & wind waste
[1] Calculation: NPP = nuclear power plant; CF = capacity factor; SL = service life; MW = megawatt
Nuclear reactor: 1000 MW x 8760 h/y x 0.94 CF x 60 y SL = 494,064,000,000,000 Wh
Solar panel: 300 W x 8760 h/y x 0.25 CF x 25 y SL = 16,425,000 Wh
1000 MW NPP equivalent = 494,064,000,000,000 Wh / 16,425,000 Wh = 30,080,000 panel
Wind turbine: 1.67 MW x 8760 h/y x 0.35 CF x 25 y SL = 128,005,500,000 Wh
1000 MW NPP equivalent = 494,064,000,000,000 Wh /128,005,500,000 Wh = 3,860 turbines
3,860 turbines x 3 blades per turbine = 11,579 blades
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