PROBABILISTIC, POSSIBILISTIC AND DETERMINISTIC SAFETY ANALYSIS

Nuclear Applications

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PREFACE

"Do not go where the path may lead; go instead where there is no path and leave a trail."
Ralph Waldo Emerson

This work covers the field of probabilistic, possibilistic and deterministic safety analysis. The material is general and addresses the interests of engineers and physicists in different fields of science and engineering. It emphasizes the nuclear applications of the covered methodologies.

Nuclear energy is being reconsidered in addition to wind, tidal and solar energies as the clean non-carbon and green energy options for what is referred to as the post-petro economy. The threat of global climatic change came along and the world woke up to the fact that burning fossil fuels for a planet with 8 billion energy hungry souls longing to emerge from poverty just was not the only option.

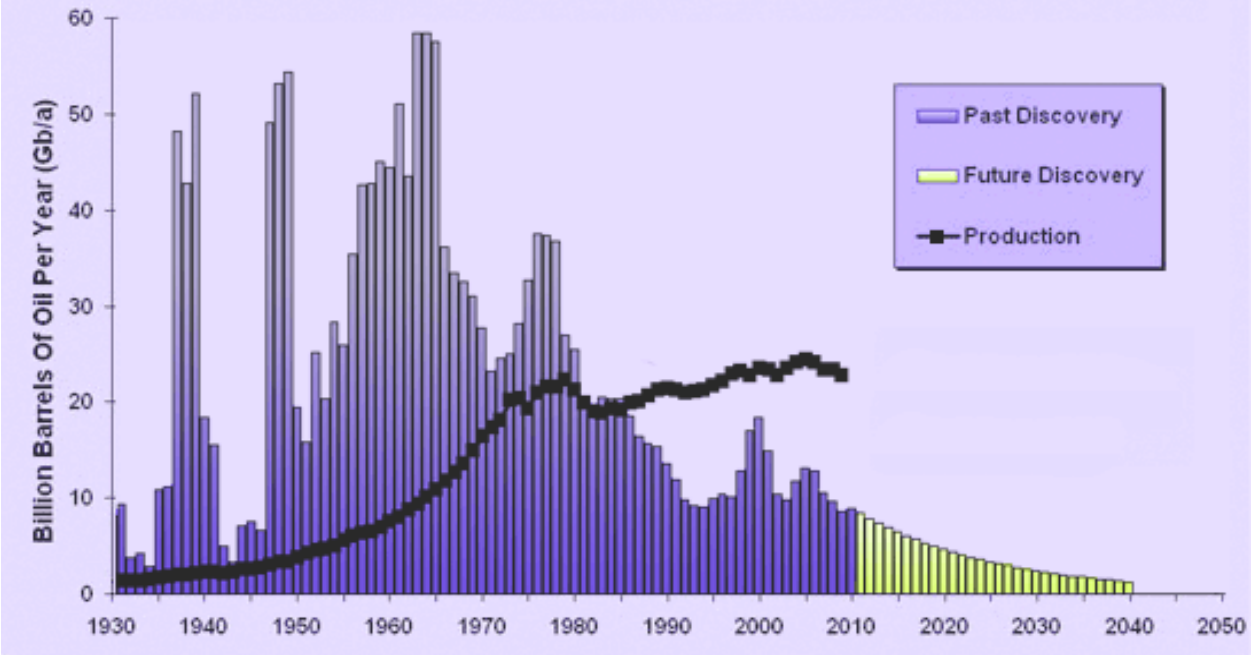

Figure 1. Growing gap between conventional petroleum production and new discoveries. Production is reaching a peak suggesting a need to switch to non-carbon nuclear and renewables sources. The shale oil and gas fracking and horizontal drilling may be a short-lived last hurrah and an exit party for the petroleum age. "Peak Oil" does not mean the end of the petroleum supply, but it means a decreased availability, hence decreased production and use and the necessity of its substitution with other energy sources.

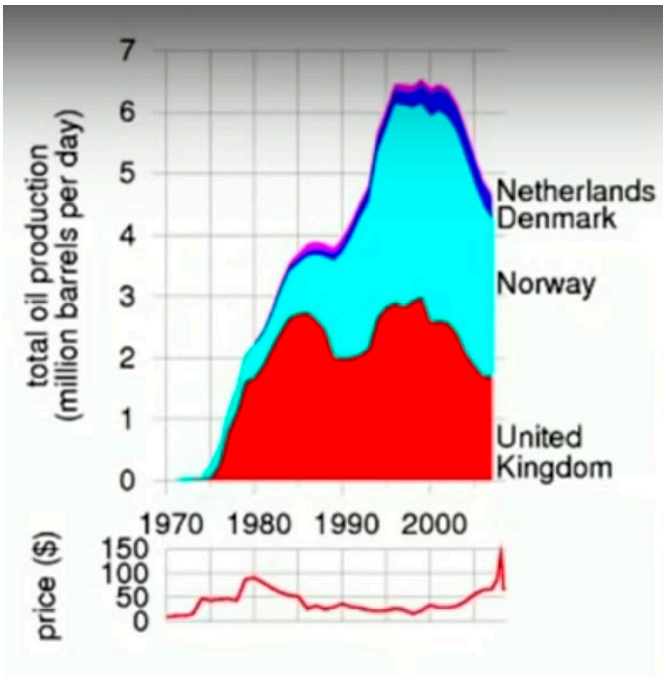

Figure 2. Peak Oil, North Sea: UK, Norway, Denmark, and Netherlands. Source: David MacKay.

NUCLEAR POWER TRENDS

The Statistical Review of World Energy shows that nuclear power generation is growing globally, setting a new record high in 2024. Global nuclear generation reached 2,817 TWhr in 2024, surpassing the previous record from 2021, with most growth coming from non-OECD countries.

The global nuclear landscape is diverging. Some countries are doubling down, driven by the twin imperatives of energy security and climate action, while others are walking away. The center of gravity is moving away from traditional Western producers toward nations prepared to back nuclear with long-term capital and policy support.

Asia Pacific, led by China's 13 percent annual growth rate, accounts for 28 percent of global nuclear output.

Eastern Europe and the United Arab Emirates UAE expanded nuclear capacity. Western Europe and North America faced stagnation, retirements, or policy-driven phaseouts. China is developing the thorium fuel cycle.

NORTH AMERICA

The USA leads the world in nuclear output at 850 TWhr annually or 29.2 percent of the world's total nuclear output.

A financial bubble in Large Language Models LLMs or Artificial Intelligence AI is feeding a frenzy in the USA for construction of duplicate Data Centers using Small Modular Reactors SMRs. These impose a huge demand on the local electrical grids as well as the limited water cooling supplies and are vehemently opposed by local communities. They require higher

enrichment in uranium in their cores to reduce their size. The have been tried in the past and have evolved into the existing systems taking advantage of the economies of scale. Their future is not yet assured to be reliable contributors to the electrical power needs.

The years 2023 and 2024 with the startup of Vogtle Unit 3, followed by Unit 4 in the state of Georgia. The two new reactors added more than 2,200 MWe of capacity to power over a million homes.

Canada's output slipped from 106 TWhr in 2016 to 85 TWhr in 2024.

Mexico, a small player, has year-to-year swings.

EUROPE

France has seen its nuclear electrical output fall from 442 TWhr in 2016 to 338 TWhr in 2024, hampered by maintenance issues and political uncertainty.

Germany completed its nuclear phase-out following the Fukushima accident, opting highly polluting brown coal.

Belgium, Switzerland, and Sweden are split between retirements and life extensions.

In Eastern Europe, the Czech Republic, Hungary, and Slovakia are increasing output.

Ukraine has managed to maintain over 50 TWhr annually despite wartime disruptions.

ASIA-PACIFIC

Asia Pacific encompasses over 28 percent of global nuclear output which is double its share from a decade ago:

China has output soaring from 213 TWhr in 2014 to more than 450 TWhr in 2024—an annual growth rate near 13 percent.

India and South Korea also posted gains on a smaller scale.

LATIN AMERICA, AFRICA, MIDDLE EAST

In Latin America, Brazil and Argentina are holding steady around 15–25 TWhr.

South Africa remains flat at about 13 TWhr.

The Middle East has a new entrant in the UAE, which ramped from zero in 2019 to over 40 TWhr in 2024 thanks to the Barakah four-units plant.

REST OF THE WORLD

Japan has restarted some reactors, but its output remains far below pre-Fukushima levels at 84 TWhr in 2024 versus more than 300 TWhr in 2010.

Taiwan, like Germany is phasing out nuclear power, with production falling from 42 TWhr in 2016 to 12 TWhr in 2024.

Pakistan and Iran continue steady modest growth.

NATIONAL ENERGY EMERGENCY, 2025

President Donald Trump laid out a sweeping energy agenda through a series of executive orders on January 20, 2025. Efforts to mitigate climate change are de-emphasized and focus is switched to immediate fossil-fuel projects, challenging the observation that petroleum and natural gas production levels are based on market conditions, more than on political decisions.

1. Energy emergency

A “National Energy Emergency” is declared, arguing that the USA faces a “precariously inadequate and intermittent energy supply, and an increasingly unreliable grid” that threatens national security.

Electricity demand is expected to surge in the coming years from data centers that support Artificial Intelligence AI and the expansion of domestic manufacturing. The largest grid operator in the USA, PJM Interconnection, warned it could face electricity shortfalls as coal plants are retired faster than new capacity is connected to the grid.

Federal agencies are directed to identify and exercise any lawful emergency authorities available to them to facilitate the production, transportation, refining and generation of domestic energy sources. Federal agencies are ordered to use all emergency authorities available to expedite new energy infrastructure projects.

2. Climate commitments

The USA withdrew from the Paris climate agreement. The international treaty sought to limit rising global temperatures to 1.5 Degrees Celsius above preindustrial levels. That level may have already been reached. Goals that aimed for half of new cars sales to be Electric Vehicles, EVs for the electric grid to be free of carbon releases, and for the economy to produce net-zero emissions, are cancelled.

The USA is responsible for around 11 percent of global greenhouse gas emissions, second in rank behind China.

3. Oil Drilling, natural gas exports

The ban on oil and gas drilling in most USA coastal waters is cancelled. The production of natural resources in Alaska is prioritized as well as the development of Liquefied Natural Gas (LNG) projects for export, particularly to Europe. Federal Government to expedite permitting and leasing of energy projects.

The USA is already the top global producer of both petroleum and natural gas. Since 2016, production of USA oil has gone up by 70 percent with the introduction of horizontal wells drilling and hydraulic fracturing (fracking) technologies in tight hydrocarbon formations. Liquified Natural Gas (LNG) exports have gone from almost nonexistent in 2016 to the USA becoming the global lead.

"We will bring prices down, fill our strategic reserves up again, right to the top, and export American energy all over the world." "We will be a rich nation again, and it is that liquid gold under our feet that will help to do it."

4. Clean energy incentives

Federal agencies are directed to pause the disbursement of funds under the "Green New Deal", a reference to the “Inflation Reduction Act” policy that channeled funding into clean energy projects. A halt to funding electric vehicle charging stations was instigated. Subsidies and other policies that favor electric vehicles are cancelled.

Wind power energy production, which is primarily controlled in the USA by foreign entities, was particularly targeted in a judicious stand-alone executive order. These commercial companies riled up USA environmental groups and caused the birth of a Not In My Own

Backyard NIMBY movement. They are accused by members of the public of seeking obscene tax profits and being insensitive to USA environmental considerations, industrial projects siting and individual property rights principles. They are accused of conspiring in suppressing free speech and honest criticism of their questionable practices and instigating intellectual property rights theft (IPT) and copyright infringement, prohibited by USA Federal Laws, through obscene bribery and instigating Intellectual Property Theft IPT.

New or renewed leases for offshore and onshore wind projects are suspended. The leasing of wind power projects on the outer continental shelf is halted. Incidentally, Enercon, a prominent German wind turbine and electrical flywheel energy storage equipment manufacturer, categorically refuses to be involved in any offshore wind production projects.

Policies regarding the role of nuclear energy in electrical energy production need to be addressed as part of the overall energy mix. It is recognized that all forms of available energy, including fossil. renewables and nuclear of energy will need to be optimally harnessed, not only to address the declared short-term energy emergency, but also for the long-term advancement of our technological civilization.

RESURGENCE OF SMALL NUCLEAR REACTORS SMRs DESIGNS

OKLO AURORA

The Oklo company was named the intended awardee for a Department of Defense project to deliver clean energy to Eielson Air Force Base in Alaska. The Defense Logistics Agency Energy issued a Notice of Intent to Award (NOITA), designating Oklo as the preferred provider following a competitive evaluation process. Under the proposed agreement, Oklo will design, build, own, and operate an Aurora powerhouse, a microreactor that provides both electricity and heat at the remote military base. The project is part of the Department of the Air Force's microreactor pilot aimed at improving energy resilience and reliability at national security facilities. The Aurora reactor uses fast reactor technology and is designed to operate independently from the grid, which is critical for remote sites like Eielson.

The company is in a pre-application readiness process with the NRC and plans to submit a formal license for its expanded 75-MW design. It is targeting late 2027 or early 2028 for initial operations at an Idaho National Laboratory site.

Oklo is one of eight companies eligible for the Pentagon's Advanced Nuclear Power for Installations program and is investing in fuel recycling capabilities. The company also holds about 14 GW of nonbinding agreements with data centers and industrial users.

NUSCALE POWER MODULE NPM

The NuScale Power Module NPM is the first and only small modular reactor (SMR) to receive design approval from the USA Nuclear Regulatory Commission (NRC). The NPM's design is based on proven pressurized water-cooled reactor technology, and was developed to supply energy for electrical generation, district heating, desalination, commercial-scale hydrogen production and other process heat applications.

"NuScale SMRs provide all the benefits of traditional nuclear energy at a lower cost and with a smaller geographic footprint. Leveraging proven technology and extensive investment, the

NPM is the only SMR technology on the market that is ready to deploy worldwide."

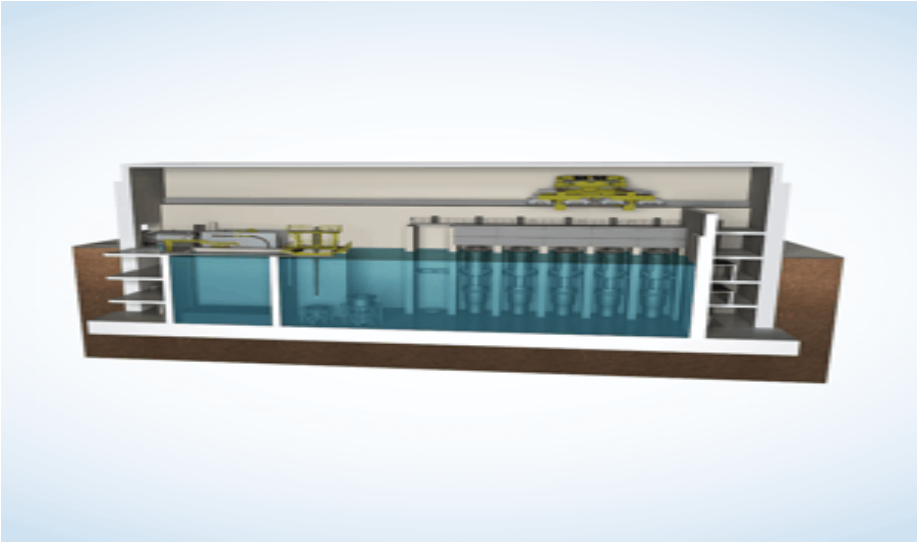

Figure 3. A 12-module plant can generate up to 924 MWe of carbon-free electricity. It can be used to power data centers, provide process heat, replace retiring coal plants, or power emergency micro-grids. Following a catastrophic loss of infrastructure, a 12-module plant can power a mission critical facility micro-grid at 154 MWe for 12 years without new fuel. https://www.nuscalepower.com/products/nuscale-power-module

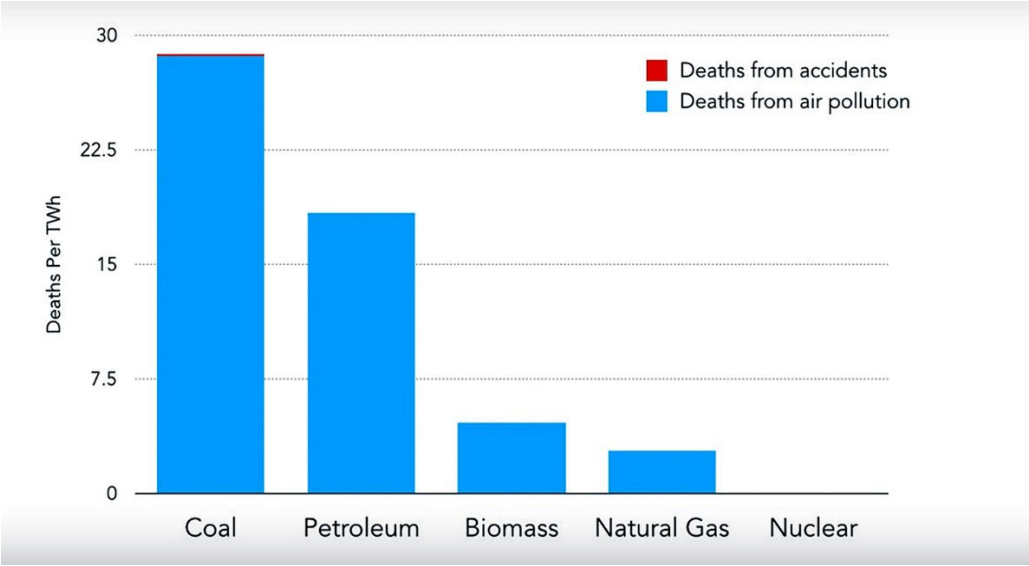

Figure 4. Risks from different energy sources. Source: Michael Shellenberger, The Lancet.

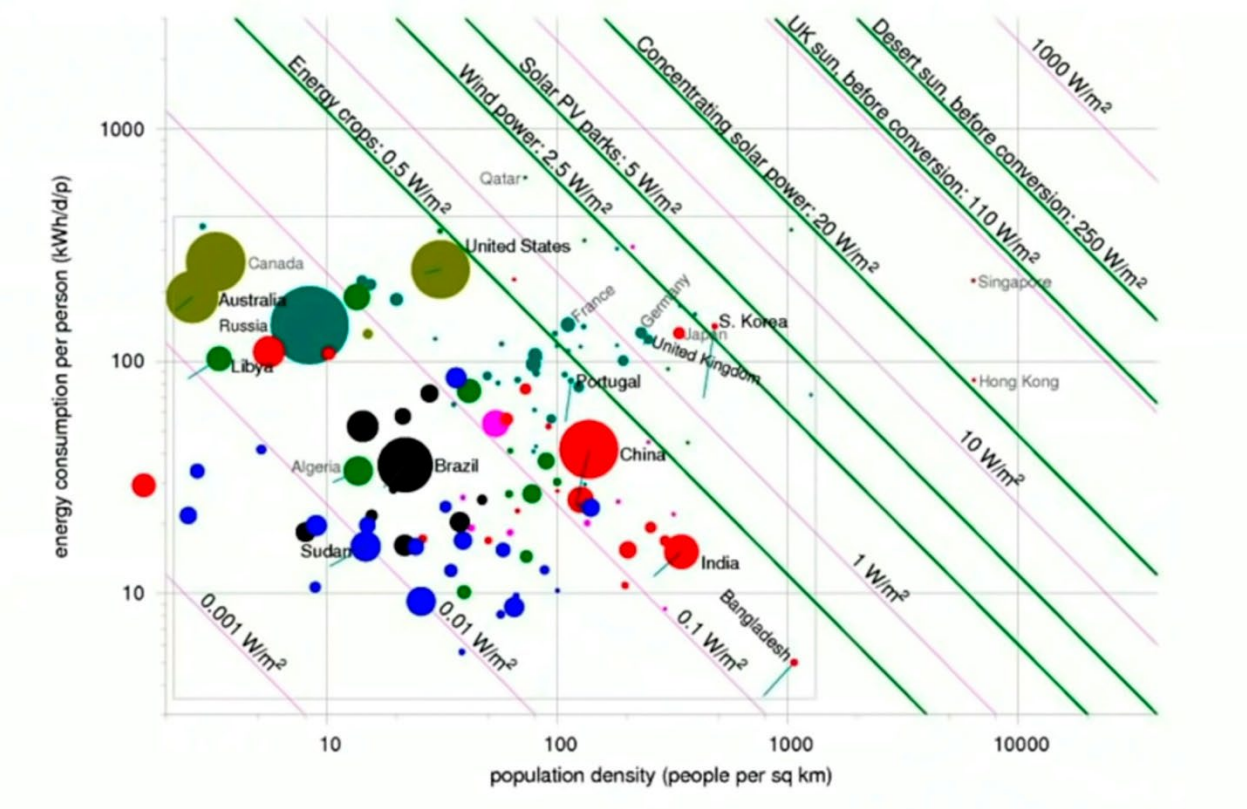

Figure 5. Only Nuclear Power at 1,000 Watts/square meter and a combination of renewables can satisfy future global energy needs from the perspective of land area availability. Logarithmic scale. Source: David MacKay.

Table 1. Power fluxes of different energy options.

Energy option	Power flux [Watts / m^2]
Rain-water, highlands	0.24
Energy crops, biomass, plants	0.5
Wind power	2.5
Tidal pools	3.0
Tidal stream	8.0
Solar Photo Voltaic panels(PV)	5.0-20.0
Concentrated thermal solar power, deserts	15.0-20.0
Solar power, before conversion (UK)	110.0
Desert areas sun, before conversion	250.0
Nuclear electricity	1,000.0

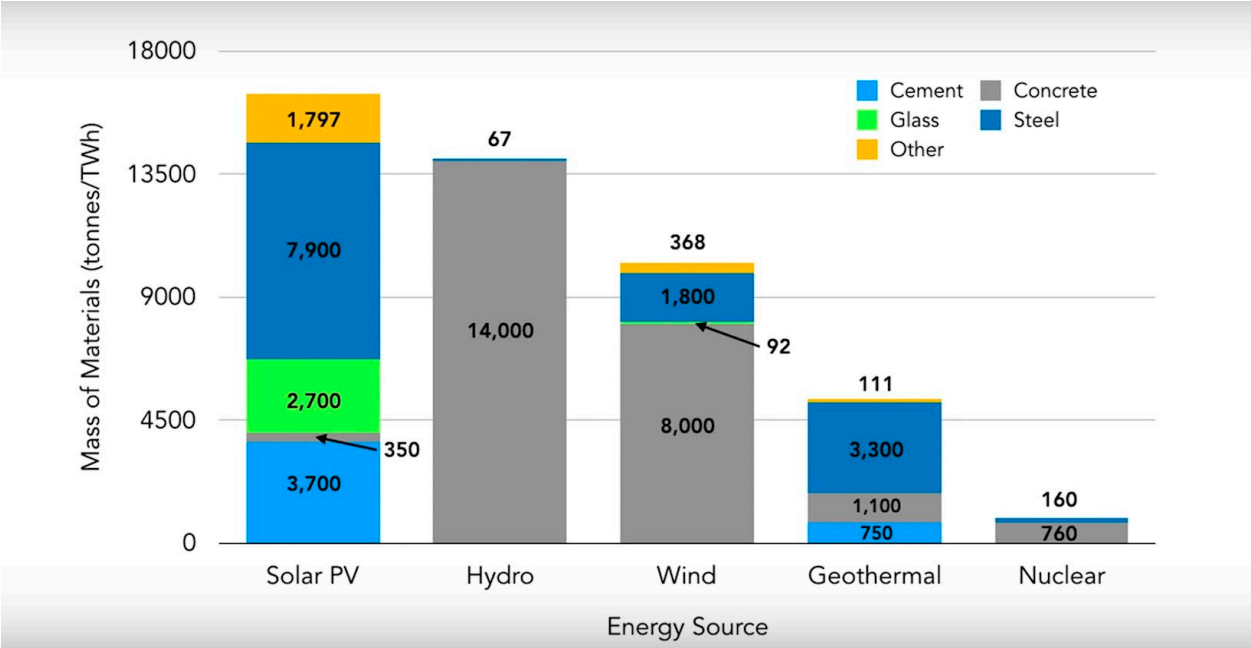

Figure 6. Materials needs of different energy sources. 1 TW = 1 Terawatt = 1 trillion Watt = 10^{12} Watt). Source: USDOE.

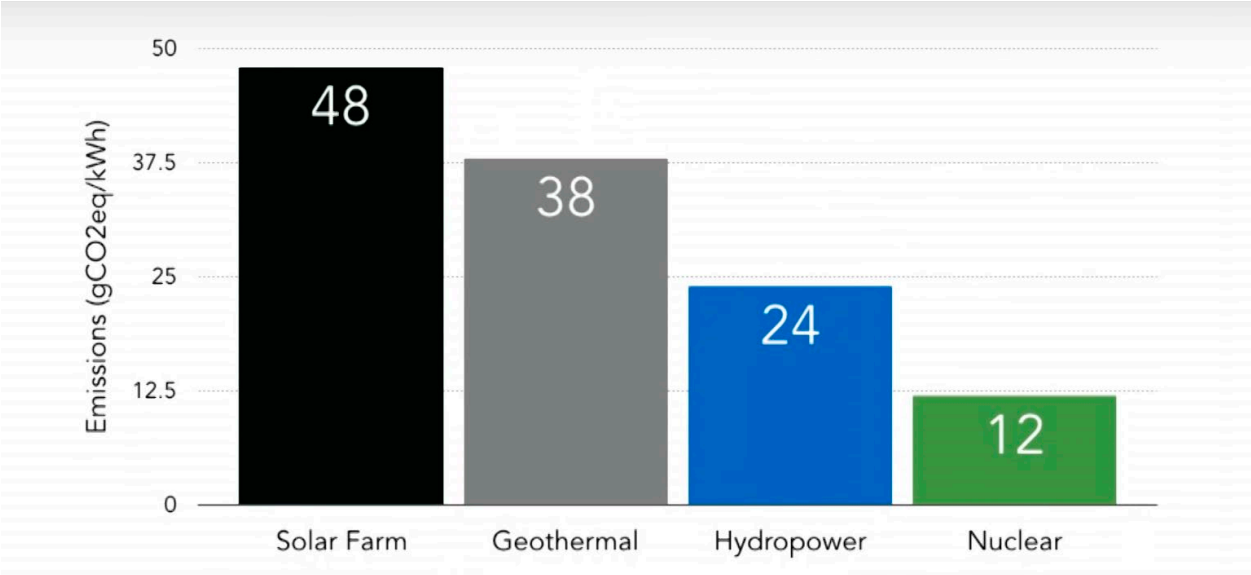

Figure 7. Carbon emissions from different sources. IPCC 2014.

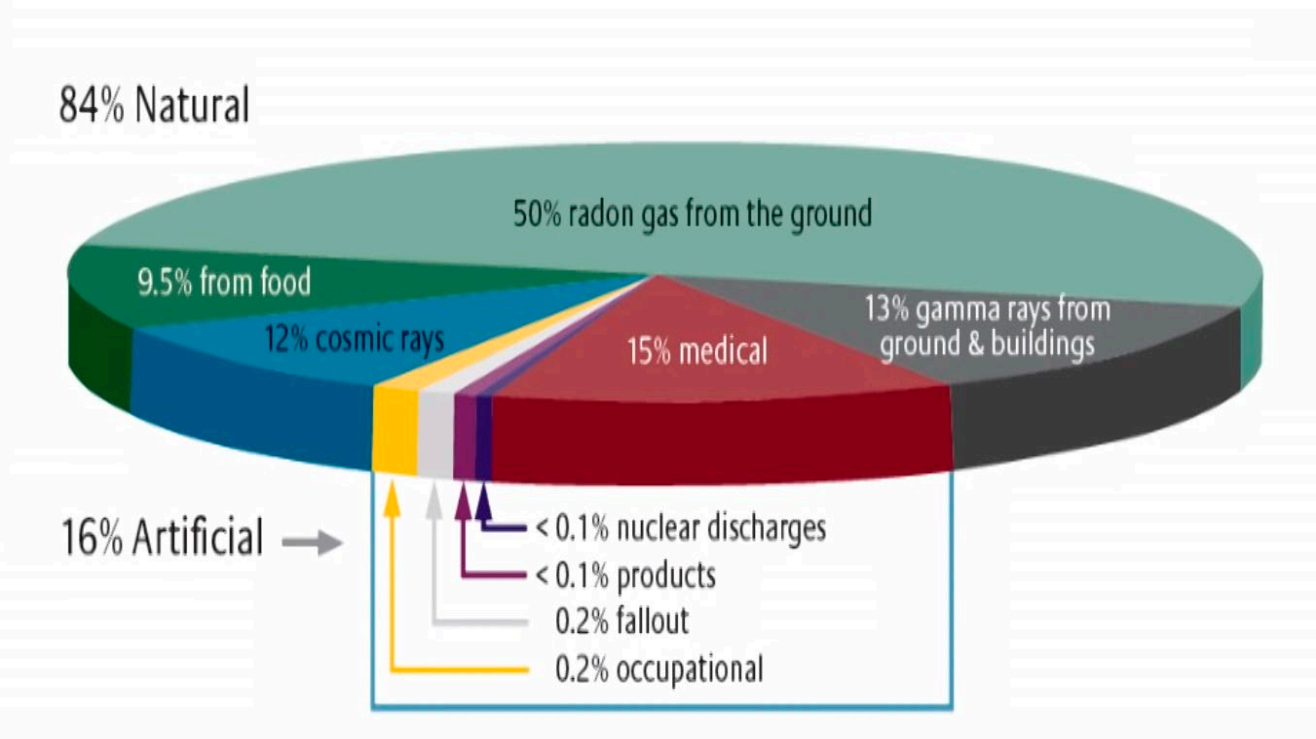

Figure 8. Ionizing radiation sources different sources. Source: Gerry Thomas, Imperial College, London.

James Lovelock, the British environmental scientist, in his book: "The Revenge of Gaia," has come to the hard conclusion that the unprecedented challenge of global warming leaves us no choice but to make a massive global investment in nuclear power, which emits no greenhouse gases. Lovelock places the risks of different energy alternatives into perspective when he considers China's Yangtze Dam, a huge source of clean hydroelectric power: "If the dam burst, … perhaps as many as a million people would be killed in the wave of water roaring down the course of the Yangtze River."

Nuclear power is economically competitive to other sources of energy.

As far as carbon emissions, nearly 700 million additional tons of carbon dioxide would be released into the atmosphere every year without nuclear power; the equivalent of the exhaust from 100 million automobiles. In comparison, the Clean Air Council reports that coal power plants are responsible for 64 percent of sulfur dioxide SO_x emissions, 26 percent of nitrous oxides NO_x and 33 percent of mercury emissions in the USA. A coal fired plant releases 100 times more radioactive material as uranium, thorium and their daughter radioactive nuclides in the particulate ash released, than an equivalent nuclear reactor.

The recent USA Global Nuclear Energy Partnership (GNEP) has several goals. One is to reduce nuclear proliferation by providing fuel suitable for nuclear power plants; but not nuclear weapons, to nations willing to submit to international oversight and safeguards. Another goal is to reduce the volume of nuclear waste by reprocessing spent fuel so that part of it can be reused. The GNEP would not eliminate the need for a nuclear waste disposal site like Yucca Mountain in the USA, but it could mean that whatever waste is generated will have a much shorter

radioactive life.

The next generation of nuclear reactors known as Generation IV designs, are safer, more reliable and more versatile than the current ones. They are applicable to applications in the coming hydrogen economy and fresh water production from sea water.

Regarding safety, while nothing is 100 percent risk free, paraphrasing Patrick Moore, if we banned everything that is potentially risky, humans would never have harnessed fire. When a reactor core melted down at Three Mile Island, the containment system did just what it was designed to do and prevented radiation from escaping to the environment. There were no worker injuries nor deaths, and none among the nearby residents. No one has ever died of a radiation related accident in the history of the USA civilian nuclear reactor program. In comparison, 100 coal miners die each year in the USA in coal mine accidents and another 100 die transporting it. Considering the Chernobyl accident, the RBMK-1000 reactor design had no containment vessel, was an inherently unstable design at low power, and its operators literally blew it up by sidestepping the established safety rules. The United Nations (UN) Chernobyl Forum reported that 56 deaths could be directly attributed to the accident, most of those from radiation or burns suffered while fighting the ensuing fire.

According to PBS's "Frontline," between 1931 and 1995 some 33,134 fatalities occurred in the USA coal mining industry. In the USA civilian aviation between 1938 to the present there has been more than 54,000 fatalities. There have been no deaths historically with civilian USA nuclear power.

The Not In My own Back Yard or NIMBY objections about nuclear plants are fading in favor of economic development. About Entergy's Grand Gulf Nuclear Generating Station near Port Gibson, Mississippi, Michael Herrin, pastor of Port Gibson's First Presbyterian Church commented: "In this town, the dragon is unemployment. Entergy is the hero." Entergy is the local electrical utility.

A typical 1,000 MWe reactor of the world's 446 nuclear power plants provides electricity to 700,000 typical homes and uses just five pounds of uranium which amounts to a 2 inch cube of pure uranium per day. A fossil fuel power plant of the same capacity burns 20 million pounds of coal using 200 million pounds of air, yielding an equal weight in polluting particulate ashes and gases that are disposed of by dilution in the Earth's atmosphere.

Globally, within 20 years, growth in electricity demand is expected to add 5,000 billion kilowatt-hours to annual electrical consumption. This would require either burning 10 billion barrels of oil annually, or three billion tons of coal per year. Alternatively this would require mining just 150,000 tons of uranium yellowcake or U_3O_8. Supplying that amount of electricity would require one million more of the largest solar arrays currently deployed.

Globally, nuclear power is an existing success and provides 78 percent of France's electricity, 58 percent of Belgium's, 50 percent of Sweden's, 40 percent of South Korea's, 37 percent of Switzerland's, 31 percent of Japan's, 27 percent of Spain's and 23 percent of the UK's. Overall, 30 percent of the entire European Union's electricity is generated by nuclear power.

By 2019 there were 97 plants in operation with aging plants being retired, and plants facing economic competition from natural gas and wind power. Planning for building over 30 new nuclear power plants would provide electricity to about 30 million typical American homes.

The 1979 Three Mile Island reactor accident which caused no deaths, no injuries and resulted in an irrelevant radiation exposure that is 1/6 of a typical chest x ray to the two million

residents in the area around the reactor. A World Health Organization (WHO) report showed that 56 deaths could be directly attributed to the Chernobyl accident. The amount of radiation from the accident was just slightly higher than background radiation and there is no indication of higher rates of cancers in the Chernobyl population than any other population. This can be compared with the industrial explosion in Texas City, Texas, that triggered a massive fire at an oil refinery and caused the death of 500 people, but did not stop oil exploration, drilling, and refining.

The USA Department of Energy (DOE) projects a 45 percent growth in electricity demand by 2030, suggesting 35 to 50 new nuclear plants will be needed by then just to maintain the nuclear energy share of the electricity market around 20 percent. T

Europe in particular is poised to begin a new nuclear age, reversing two decades of policies aimed at abandoning nuclear power as an energy source following the Chernobyl accident in 1986. Driving the turnaround are high oil and gas prices, possible peak oil, climate change worries; and concerns about the reliability of supplies from Russia, which provides 25 percent of Europe's natural gas and 12 percent of its oil. The UK wants to replace some of the 18 aging nuclear plants that are due to be shut down by 2023. Finland is building the first new nuclear generating plant in Western Europe since 1991. Sweden, Italy and the Netherlands have either abandoned plans to phase out old nuclear plants or opened discussions on construction of new ones. Switzerland has lifted a moratorium on new plants. Italy, which shuttered its four nuclear plants after Chernobyl, is Europe's biggest energy importer has plans to buy power from a plant under construction in France. Poland agreed to help build a plant in Lithuania. It will provide power to Latvia and Estonia, in addition to Poland and Lithuania. Belarus plans the construction of a plant that would begin generating power in 2014 and plans additional units by 2025.

France is almost entirely powered through nuclear and hydroelectric power and has some of the lowest CO_2 emissions rates in the world. Germany has invested in wind and solar energy and is reconsidering a decision to close its nuclear power plants. It is phasing out its old nuclear power plants after Fukushima. If it still thinks it can lower its carbon emissions, this places it in an impossible situation.

Even though nuclear power accounts for just 20 percent of the USA's electrical energy, it provides 80 percent of France's electricity needs; 79.9 percent of Lithuania's; 55 percent of Belgium's; and 50 percent of Sweden's. China has built 9 new reactors since 1991, with plans to accelerate its nuclear power program. India is building 8 reactors. Half of the Ukraine's energy comes from the nucleus despite the Chernobyl reactor accident. Russia has 31 reactors at 10 nuclear power plants sites, accounting for 16-17 percent of its electricity generation and plans to increase the proportion of nuclear-generated power to at least 25 percent by 2030.

As of 2019, there were 448 nuclear reactors worldwide in 31 out of 200 countries producing 370.22 GWe of electricity, of which 97 were in the USA. They provided 14 percent of the electrical energy produced globally.

Forty eight additional nuclear plants were under construction and 60 reactors are in the planning stage. Thirteen countries that already have nuclear capacity, and 10 that do not, were in the process of building new reactors. The new reactors would double the existing installed capacity.

The chapters in this work are self-contained and can be read in the order that the reader wishes. The work is still in progress and is evolving and is frequently being updated. It is continually "under construction." In fact, it is an ongoing experiment that started in 1998. The

suggestions by Reier Groven are thankfully acknowledged.

The hope is that this modest effort will contribute to the scientific literacy of the readers in the safety analysis area of knowledge, and satisfy their intellectual curiosity about our universe and our world, whose better future we all dream about.

Dr. Magdi Ragheb

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